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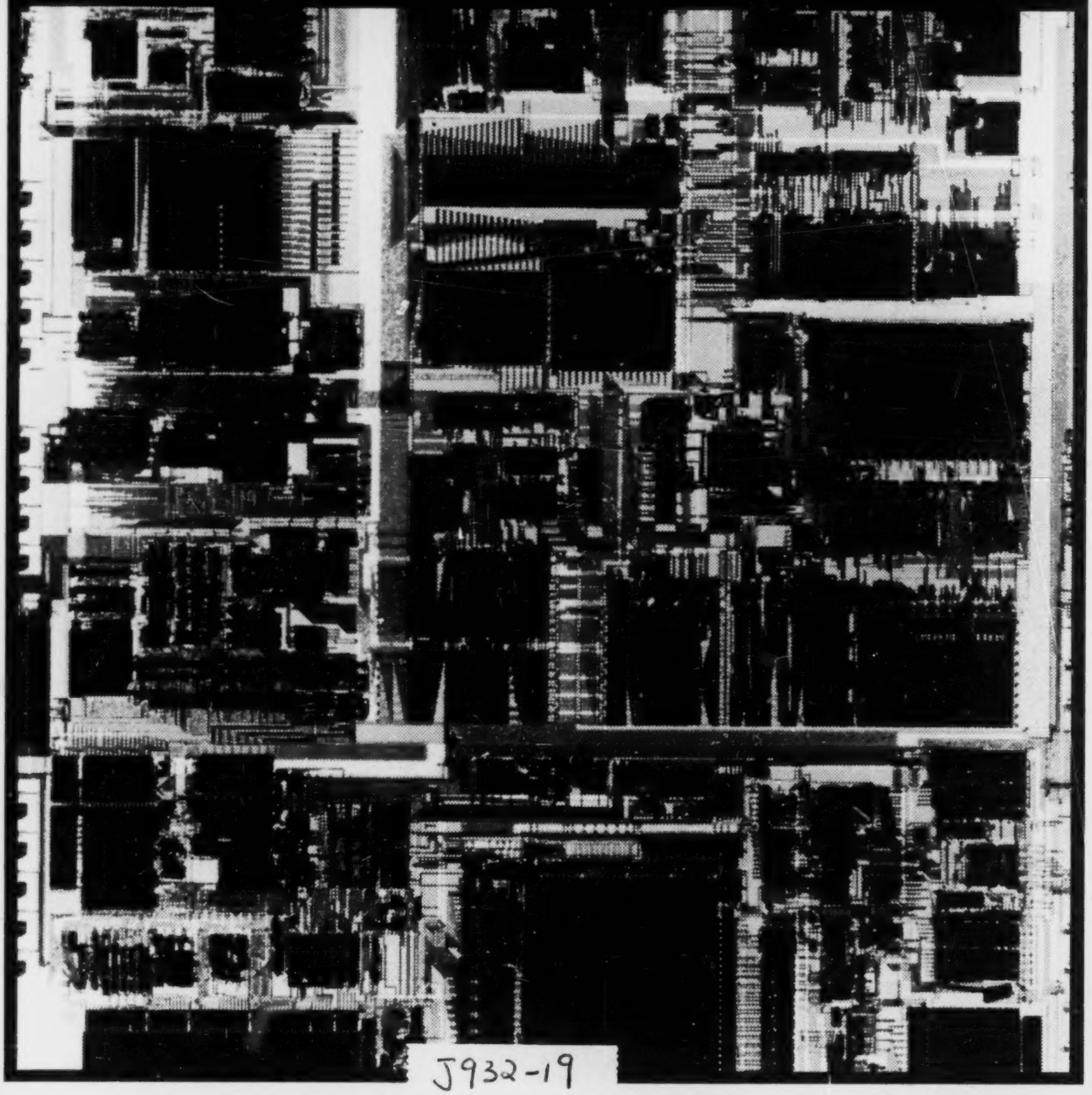
The Benefits and Risks of Federal Funding for Sematech



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A SPECIAL STUDY

THE BENEFITS AND RISKS OF FEDERAL FUNDING FOR SEMATECH

The Congress of the United States
Congressional Budget Office

NOTE AND CREDIT

Details in the text and tables of this report may not add to totals because of rounding.

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PREFACE

Sematech is a proposed industrywide research consortium aimed at advancing the technology with which semiconductors are manufactured. The Congress will soon decide whether the federal government will participate in the consortium, and what form that participation would take. In response to a request by the Senate Commerce Committee, this paper analyzes the potential benefits and risks of federal involvement in Sematech. In keeping with the Congressional Budget Office's (CBO's) mandate to provide nonpartisan analysis, no recommendations are made.

The report was written by Philip C. Webre of CBO's Natural Resources and Commerce Division under the supervision of Everett M. Ehrlich and Elliot Schwartz. Peter Glick, Andrew Horowitz, Colleen Loughlin, Lisa Najarian, and Susan Punnett provided valuable research assistance. The author wishes to thank Thomas Dorsey, Wayne Glass, W. Edward Steinmueller, Richard Van Atta, and James Whitt for helpful comments. The report was edited by Sherry Snyder, assisted by Nancy H. Brooks. Kathryn Quattrone typed the manuscript and prepared it for publication.

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GLOSSARY

The following definitions of terms are based on Daniel Okimoto, Takuo Sugano and Franklin Weinstein, eds., *Competitive Edge: The Semiconductor Industry in the U.S. and Japan* (Stanford, Calif.: Stanford University Press, 1984), and Department of Commerce, Industry and Trade Administration, *A Report on the U.S. Semiconductor Industry* (September 1979). One very good guide to semiconductors is the September 1977 issue of *Scientific American*, which was devoted entirely to microelectronics.

Application-specific integrated circuit (ASIC)	An integrated circuit designed for one narrow use, such as substituting one large integrated circuit for many small ones. Often custom or semi-custom.
Bipolar	One of the two types of transistors and integrated circuits; the other is metal-oxide semiconductor (MOS). They are faster than MOS devices but more difficult to make.
Bit	A zero (0) or one (1) in the binary language of computers.
Byte	Eight (8) bits.
Captive producer	A semiconductor manufacturing firm that produces exclusively for in-house consumption. Contrasts with merchant producer.

Custom circuit	An integrated circuit designed and manufactured for a particular customer. Contrasts with semi-custom, which has only the last few manufacturing steps tailored to customers' specifications. Also contrasts with integrated circuits of standard design, which are produced in volume for many users.
Die	The small piece of the wafer on which an individual semiconductor device has been formed.
Diffusion	A semiconductor manufacturing process in which desired impurities are introduced into the silicon by baking the silicon wafers at high temperatures and pressures in chemically altered atmospheres. A less precise alternative to ion implantation.
Digital integrated circuit	An integrated circuit that uses binary codes (0's and 1's) to store and manipulate data by using the on/off properties of transistors. Contrasts with linear integrated circuits.
Diode	A discrete semiconductor device that allows electricity to flow only in one direction.
Dynamic random access memory (DRAM)	A type of RAM that requires some external support circuitry. Contrasts with static random access memory. Categorized by speed and memory capacity.
Epitaxy	A semiconductor manufacturing process in which a layer of silicon is grown on the surface of a silicon wafer. This new layer is grown because it possesses a unique crystalline structure or other desirable feature not found on the wafer itself.

Erasable programmable read only memory (EPROM)	A memory device that can be read but not written to. Unlike other programmable memories, it can be erased (by exposing it to ultraviolet light) and reprogrammed.
Etching	A semiconductor manufacturing process in which acid is used to remove previously defined portions of the silicon oxide layer covering the wafer to expose the silicon underneath. Removing the oxide layer permits the introduction of desired impurities into the exposed silicon through diffusion or ion implantation.
Gallium arsenide (GaAs)	A compound semiconductor material that allows transistors and integrated circuits to operate much more rapidly than similar devices made of silicon. Much more difficult, and hence more expensive, to manufacture than silicon.
Gate array	A kind of semi-custom circuit.
Geometries	The size of the smallest feature on an integrated circuit, usually the connections between transistors. At present, most new integrated circuit designs have geometries between 1.0 and 1.5 microns, although some new memory devices have smaller geometries.
Integrated circuit (IC)	A complete electronic circuit, composed of interconnected diodes and transistors, fabricated on a single semiconductor substrate, usually silicon. Also called a chip.

Ion implantation	A semiconductor manufacturing process in which the silicon is bombarded with high-voltage ions in order to implant them in specific locations and provide the appropriate electronic characteristics. A more precise alternative to diffusion.
Linear integrated circuit	An integrated circuit that creates and processes an internal analog of the signal it is receiving. Contrasts with a digital integrated circuit which reduces the signal to a series of 0's and 1's. Used typically in consumer goods, communications equipment, and scientific instruments.
Lithography	A semiconductor manufacturing process in which the desired circuit pattern is projected onto a photoresist coating covering the silicon wafer. When the resist is developed, like an ordinary photograph, selected portions of the resist come off, thus exposing parts of the wafer for etching and diffusion.
Logic circuit	A type of digital integrated circuit that performs certain logical or mathematical functions and often provides connections between other major parts of computers.
Memory device	An integrated circuit that stores binary data. Categorized according to accessibility (at random or serially), size, speed, and to whether it can be written to or is read only.
Merchant producer	A semiconductor manufacturing firm that produces primarily for sale on the open market. Contrasts with captive producer.

Metal-oxide semiconductor	One of the two types of transistors and integrated circuits; the other is bipolar. It is simpler to fabricate and hence is often used in manufacturing large, dense integrated circuits. On the other hand, it is slower than bipolar and sensitive to radiation, which limits its military applications.
Metalization	A semiconductor manufacturing process in which a layer of metal, such as aluminum, is placed on the wafer to connect the transistors and diodes within an integrated circuit.
Micron	A micrometer, or one-millionth of a meter.
Microprocessor	An integrated circuit that performs the function of a central processing unit of a computer.
Optical lithography	Lithography that uses ordinary or ultraviolet light to expose the circuit pattern. Currently the most commonly used technology. Contrasts with X-ray lithography.
Photomask	The template (usually made of quartz) containing the circuit pattern that is used in lithography to define the areas for etching in the photoresist.
Photoresist	A light-sensitive chemical used to coat silicon wafers during lithography. The photoresist makes the wafer like a photographic negative. The integrated circuit pattern is projected onto the coated wafer, and then the wafer is developed.

Photovoltaic cell	A specialized diode that turns light into electricity. Used in space and other remote applications. Becoming common in some consumer uses.
Random access memory (RAM)	A memory device whose individual memory cells can be read from or written to at random (that is, not serially).
Read only memory (ROM)	A memory device whose contents can be read from but not written to.
Semiconductor	A material that is neither a good insulator nor a good conductor; usually silicon, germanium, or gallium arsenide. The term has come to refer to all devices made of semiconducting material, including integrated circuits, transistors, and diodes.
Semi-custom circuit	An integrated circuit that has the initial phases of its fabrication standardized, but allows the later stages to be tailored to suit the individual customer.
Silicon	A semiconducting material commonly used in semiconductor devices because it is so easy to work with.
Static random access memory (SRAM)	A type of RAM that has self-contained memory circuitry. Contrasts with dynamic random access memory. Categorized by speed and memory capacity.
Synchrotron	A type of particle accelerator being discussed as a potential source of X-rays for use in X-ray lithography.

Transistor	A three-terminal semiconductor device used mainly to amplify or switch. Its invention at Bell Laboratories in 1948 started the semiconductor revolution.
Wafer	When most semiconducting material is purified, it comes out in long sausages between 1 and 8 inches in diameter, which are then sliced into wafers, roughly 1 millimeter thick. The wafer is then used as the substrate for forming semiconductor devices.
Wafer stepper	A type of lithography equipment that exposes the wafer one die at a time, instead of the whole wafer at once.
X-ray lithography	An emerging type of lithography that uses X-rays instead of light to expose the circuit patterns on the wafer.

SUMMARY

Observers within and outside the U.S. semiconductor industry have called for a response by the federal government to the perceived declining competitiveness in that industry. The centerpiece of these proposals for federal action is Sematech--a research consortium of U.S. semiconductor producers and suppliers of semiconductor manufacturing equipment. As currently envisioned, Sematech would receive almost half its funding from the federal government--a total of about $600 million over the next six years. The aim of Sematech is to improve the manufacturing technology of the U.S. semiconductor industry (particularly that used in the production of integrated circuits), an area of widely acknowledged weakness. The Sematech proposal raises many important issues; one set of questions centers around the public interests at stake and whether federal intervention is warranted or appropriate; another set centers around whether Sematech would address these interests.

THE SEMATECH PROPOSAL

Current plans for Sematech center on a six-year, $1.5 billion, three-phase effort. The intent is to improve the equipment, materials, and techniques involved in the manufacturing process, as opposed to improving the design of semiconductor devices themselves. A production line will be built to prove and integrate the technology, but actual full-scale manufacturing is left to individual semiconductor companies. Sematech's near-term focus is on improving current commercial practices rather than on developing entirely new materials or technology for the industry.

Funding for the consortium would come from private firms and from federal, state, and local governments. Membership by private firms is limited to U.S. capital-affiliated semiconductor companies and semiconductor manufacturing equipment (SME) producers. Member companies are expected to account for roughly half the total funding. The federal government would contribute about $100 million annually, and the state and local governments in which the Sematech facility is located are also expected to contribute. The goal of Sematech is to have commitments of roughly $250 million per year for the next six years.

Sematech has three tasks. The first is to conduct research and development (R&D) on advanced semiconductor manufacturing techniques. The second is to test and demonstrate the resulting techniques on a pilot production line. Third, Sematech would then develop processes to adapt these proven techniques so that they can be applied to the manufacture of a wide variety of other products.

The technology developed by Sematech will be given first to member firms, but will be licensed for a royalty after a suitable delay. The results will become more widely available as makers of semiconductor manufacturing equipment incorporate them into their products, and the technology will eventually spread to all semiconductor manufacturing firms, at home and abroad. Thus, the benefit to the member firms would be to have a head start on using the technology, not absolute monopoly of that technology.

THE SOCIETAL BENEFITS OF SEMICONDUCTOR PRODUCTION

The federal government traditionally relies on markets to decide how and when industries will grow and contract. Proponents of Sematech must therefore demonstrate that without federal intervention, the level of resources devoted to semiconductor research and development will be inadequate to meet society's needs. In essence, proponents must identify some type of public benefit associated with semiconductor production that accrues to the national economy but not just to individual semiconductor firms. Identifying these public benefits is somewhat subjective, but at least three types can be advanced:

- National security;
- Research and development spillovers to the whole semiconductor industry; and
- Spillovers to the economy as a whole, and, more generally, to the national science infrastructure.

National Security

U.S. military strategy relies on having fewer, but technologically more advanced, weapons than the Soviet Union. The concern of military planners is that deterioration of U.S. semiconductor producers could soon lead either to dependence on foreign sources for components for sophisticated weapons systems, or to a decline in the technological base needed to develop and use these components. Domestic production facilities dedicated to semiconductors with military applications could be procured to overcome any dependency on foreign suppliers. If, however, the ability to use the technology is lost, such facilities would be irrelevant to future generations of semiconductor technology. The alternative--using either devices made by foreign firms or devices produced in the United States under foreign license--may reduce the flexibility of U.S. foreign policy or may compromise the U.S. advantage in military technology. Sematech may have a role to play in maintaining a sound and up-to-date technological base.

Spillovers Within the Industry

From the semiconductor industry's perspective, investing in innovative design research often brings a greater return than focusing R&D efforts on better manufacturing processes. Many firms spend a great deal of effort duplicating (or "reverse engineering") products manufactured by other companies. The existence of these so-called imitators reduces the incentives for innovative firms to perform R&D. Such firms may underinvest in R&D because a substantial part of the benefits from their discoveries might be captured by imitators. Moreover, this pattern biases the investment choices made by U.S. semiconductor firms toward R&D projects that produce radical new devices with proprietary designs and may discourage these firms from investing in manufacturing technology, the results and benefits of which are relatively easy for others to appropriate. Federal funding could fill the investment gap in generic manufacturing technologies from which all semiconductor producers may benefit.

Spillovers to the Economy

Recent economic studies have suggested that the rate of return to society of R&D in electronics has been much greater than the return to the individual firms performing it. This evidence is consistent with case studies of innovation in other industries, which have suggested that R&D's return to society is, on average, twice that of the private return. In fact, acknowledgement of these societal benefits is reflected in the large amount ($400 million to $500 million) that federal agencies currently spend on semiconductor R&D. But most of this research is related to technologies that have either distant commercial applications (such as the use of gallium arsenide materials) or only military significance (such as radiation hardening, which allows semiconductors to function during nuclear warfare).

Science-based industries, such as the semiconductor industry, play a role akin to that of universities in building and preserving the nation's stock of human capital--that is, both scientific and engineering knowledge and the ability to expand it. The U.S. semiconductor industry thus not only creates new technology but also helps diffuse this knowledge throughout the economy.

The future of manufacturing technology will depend increasingly on the use of semiconductors in the production process. Robotic technology, for example, relies on semiconductors, as does "statistical" process control, which depends entirely on the rapid absorption, transmission, and analysis of information on production lines via semiconductors. Flexible manufacturing systems depend on electronic computers and other equipment that can be reprogrammed easily yet can perform complex tasks with precision. Thus, semiconductors are not only being incorporated into more goods, but, more to the point, they are affecting the ways in which more goods are being made.

EVALUATING THE PROGRAM

The value of the Sematech program depends on the answers to a series of questions, including:

- Would the program address the semiconductor industry's competitive shortcomings?
- Would it do so in a way that provides benefits to the economy or society in general?
- What risks does such a program present? and,

- How might the design of the program affect its ability to generate the expected social benefits?

By focusing on manufacturing technology, Sematech would be addressing an area in which the U.S. industry lags its competitors and in which existing incentives may be inadequate to encourage individual firms to conduct research that might help them catch up to those competitors. Improving manufacturing technology would lower the cost of these devices. Lower costs in turn would facilitate the application of semiconductors to other areas, such as robotic manufacturing, telecommunications equipment, and computers and other electronic goods. Although the effects of Sematech on national security would be less direct and less immediate, over the long term the military would certainly benefit from the competence of the manufacturing base fostered by Sematech.

Does Sematech Address the Industry's Problems?

It is generally agreed that the weakness of the U.S. semiconductor industry is found in manufacturing technology rather than the production of any specific devices. Thus, Sematech's focus on generic manufacturing equipment and techniques seemingly brings new resources to bear on a problem that is not being adequately addressed by either federal or private research programs. Semiconductor manufacturers spend only about $200 million to $300 million on R&D to improve their manufacturing technology. Makers of semiconductor manufacturing equipment spend another $500 million. The $250 million budgeted for Sematech's research therefore would raise spending on R&D for commercial semiconductor manufacturing in the United States by about one-third.

Does Sematech Create Public Benefits?

Sematech addresses the three areas of federal interest outlined above--national security, spillovers within the semiconductor industry, and spillovers to the economy--although to different degrees. National security goals are met by assuring an adequate supply of specific devices that are produced domestically. But Sematech cannot guarantee that U.S. semiconductor producers will suddenly find filling U.S. military requirements a profitable activity, especially considering the Defense Department's stringent bureaucratic and technological requirements that often have no civilian counterpart. Sematech, however, may increase the probability that any given technology needed by the military will be available from U.S. sources in the future.

Sematech's prospective benefits, however, should be greater in the diffusion of knowledge and new techniques, both within the semiconductor industry and to other industries. Many economists have expressed concern that research into new products proceeds more rapidly than research into improving production processes. The traditional counterargument is that equipment manufacturers have strong incentives to incorporate technological advances into the machines that they sell, and these advances are thereby incorporated into production lines. But many producers of equipment for making semiconductors are specialized and small, particularly when compared with semiconductor manufacturers themselves; they may not be able to afford significant product research. Thus, semiconductor manufacturing research may well be substantially underfunded from a societal point of view, and the societal rate of return on such research may be correspondingly high.

Moreover, improvements in manufacturing processes would lower the cost of producing all semiconductors and enhance the existing U.S. advantage in this industry--that of design--by making them more price competitive. Lower prices would allow sophisticated applications of microelectronics to diffuse more rapidly through the economy. The potential benefits of the Sematech program from an economywide perspective, therefore, may be substantial.

What Are the Risks?

A research program like Sematech bears the conventional risk associated with scientific experimentation--success is far from guaranteed. But given the likelihood that Sematech would attract highly knowledgeable and experienced personnel from its member firms, this risk should be no greater, and could be less, than that associated with a comparable private endeavor.

Sematech as a policy instrument, however, poses other risks. The most important risk concerns the rate of diffusion of Sematech's results. If those results diffuse too slowly, the program's benefits would be usurped by its member firms. But many avenues are available for disseminating findings of this type--personnel movements, professional journals and meetings, word-of-mouth, and, of course, by building these results into new semiconductor manufacturing equipment. The primary concern may be, instead, that Sematech's results would be disseminated too rapidly and become readily available to foreign producers, undermining the purpose of the program. To counter this problem, foreign firms could be refused formal access to its results (although this action might set an undesirable precedent for future trade policy). But even with rules regarding membership and access, results might be spread abroad by U.S. firms with foreign production facilities, or by U.S. SME producers who incorporate Sematech's results into their equipment and then sell it to foreign producers. Sematech's contribution to the national welfare may be reduced if U.S. capital-affiliated firms take its federally financed results and deploy them in foreign production sites.

A separate risk is that of collusion--agreements among firms to restrict trade--which is always a concern whenever firms in the same industry meet for a common purpose. Sematech could lead to collusion, for example, if its member firms were to use it as a vehicle for redefining the conventional standards for microelectronic products. Such action could create serious disadvantages for nonmember firms and provide benefits only to Sematech members. But if Sematech tried to enforce a standard that was not accepted by the market, its efforts might prove self-defeating. Given the likely diffusion of Sematech's research, however, the consortium would probably not become a barrier to competition in the semiconductor industry.

A third risk concerns centralizing the industry's research agenda. Although an industrywide consortium avoids the costs of duplicative research by individual firms, it entails the risk of creating a less diverse research program than would occur if individual firms were to spend the same level of resources. Individual firms, however, would probably not spend as much on research and development in the absence of Sematech because of the likelihood that their results would be appropriated by competitors. Thus, the research effort in Sematech may complement the R&D of individual companies and need not detract from their other research efforts.

A final risk concerns the unprecedented institutional arrangements found in Sematech. Industrywide research consortia are proving to be a popular new arrangement, but their track record is short and mixed. Similar projects have either had some measure of success--as the Microelectronics and Computer Technology Corporation has--or have had problems maintaining their cohesion, as did the semiconductor industry's Operation Leapfrog in the early 1980s. The magnitude of the financial and personnel commitments being made to Sematech, however, indicate that its members will be committed to its success.

A separate but related issue is whether the federal government will be able to stay within its role as a "silent partner." Once basic policy guidelines have been established, the government's role will be largely advisory. In many other applied research endeavors that the government funds, it determines the technological agenda (as it does in the programs of the National Aeronautics and Space Administration and the National Institutes of Health that deal with commercial technologies). But the success of Sematech may depend on the government's taking a more passive role in daily affairs.

ISSUES IN POLICY DESIGN

The design of the Sematech program will influence greatly its prospects for generating economic benefits. An immediate issue is the royalty (licensing) policy it will pursue. From a societal perspective, Sematech will succeed to the extent that its research results are spread quickly throughout the domestic industry but are slow to reach foreign producers. In practice, however, it would be difficult to channel the dissemination process, since the avenues through which technology diffuses are often the same in the United States and abroad. Moreover, it may be viewed as inequitable to give domestic firms, who had the opportunity to participate in Sematech but did not join, preferential access to its results.

The more general concern is that U.S. firms will use Sematech to increase the productivity of their foreign subsidiaries that export to the United States and thereby accelerate the movement of the semiconductor industry abroad. Inhibiting this trend may require a more detailed agreement between the government and the industry, rather than a simple royalty policy.

An additional issue is the precedent that Sematech establishes. Supporting technological advancement may be a better form of assistance to an industry than restraining trade through tariffs or quotas. But such a program runs the risk of becoming an entitlement for uncompetitive industries, even when technology would not appear to offer a solution to an industry's competitive handicaps. The government may wish to make clear its view that future protection does not logically follow from this type of program.

Finally, the Sematech program is sufficiently novel that it is not obvious where in the government it should be located and funded. The Department of Defense has a series of programs related to technological development and the semiconductor industry and is interested in preserving the technological prowess of the defense industrial base as a matter of policy. Yet its major accomplishments in semiconductor R&D consist of "driving" technology to new levels of performance with only secondary regard for cost. The department has little experience in promoting technology that has immediate commercial applications and is cost effective.

A proposed alternative to the Department of Defense is an ad hoc committee with representatives from DoD, the Department of Energy and its National Laboratories, and the National Science Foundation's Engineering Research Centers. Such a committee would reflect the broader interests of the federal government and provide more diverse expertise, but would have to be organized quickly in order to establish policy and budgetary priorities and to hire staff. The existing proposal for an ad hoc committee gives it a full-time staff of only seven; the rest would have to come from the participating federal agencies.

CHAPTER I

INTRODUCTION

A common perception, both inside and outside the semiconductor industry, is that U.S. producers are losing their competitive edge to Japanese firms. This perception has led to a number of proposals for action, the most prominent of which calls for the federal government to join in the funding of a research consortium of semiconductor producers and suppliers of semiconductor manufacturing equipment. The aim of the consortium, known as Sematech, is to improve the manufacturing technology of the U.S. semiconductor industry, an area of widely acknowledged weakness. Under the current proposal, the federal government would provide a total of about $600 million over the next six years--almost half of Sematech's total budget.

The Sematech proposal raises a series of important issues. The industry and the proponents of Sematech have focused on whether the United States has lost its competitive lead in semiconductor production to Japan. Evidence (presented in Chapter II) suggests that the lead has been lost mainly in the production of semiconductor memory devices for the open market and in some aspects of manufacturing technology. Although the advantages held by Japanese companies have yet to translate into market dominance, they could do so, if sustained. Another, and more important, issue is whether the relative decline of the domestic semiconductor industry is a matter for public concern. This is the question addressed in this report.

THE PUBLIC INTEREST IN THE SEMICONDUCTOR INDUSTRY

Change is a fact of economic life. Industries and technologies have cycles, and the fortunes of particular firms and industries--while of concern to the people most closely involved--are not typically grounds for federal intervention. Proponents of Sematech argue that the semiconductor industry is different because it contributes to the national welfare in ways that extend beyond the usual measures of output and employment. The public interest in the semiconductor industry stems from the industry's contributions to national security, to improved productivity in its own and other industries, and to the overall advancement of science. From a public policy perspective, the decision to support Sematech may hinge more on its contributions to the overall national welfare than on its narrow ability to help U.S. firms outproduce foreign competitors.

As will be discussed in Chapter III, the semiconductor industry ranks high on these measures of national welfare. Areas of national concern would include the loss of the "spillovers" provided by a dynamic semiconductor industry. These spillovers occur when the research and development performed by one firm within the industry benefits another, and as lower costs of integrated circuits in turn result in lower costs of computer, robotic, and other electronic equipment throughout the economy. Moreover, the semiconductor industry is a repository of much of the scientific and technical talent in the economy, somewhat akin to a university. Just as the decline of the nation's major universities would be a concern, so may the condition of its science-intensive industries.

In addition, semiconductors are increasingly important to U.S. weapons programs. The actual number of semiconductors consumed by the Department of Defense (DoD) represents only a small fraction of the total produced in the United States and, consequently, quantitative shortages are not likely to be the issue. But a dependence on foreign semiconductor technology might place further constraints on U.S. foreign policy and might lead to a deterioration of the technological base of the U.S. industry, upon which DoD relies.

CURRENT FEDERAL SUPPORT

The federal government is already significantly involved in the U.S. semiconductor industry. Many of the current and proposed programs of special assistance to the U.S. semiconductor industry are based on the industry's analysis of unfair foreign competition. The perception within the U.S. semiconductor industry is that U.S. producers lost this market because their industry had been targeted by the Japanese government.[1] The major elements of this alleged targeting included the closing of the Japanese market to U.S. semiconductor devices as soon as equivalent Japanese devices became available, Japan's Very Large Scale Integration (VLSI) cooperative research project (in which the government provided seed money for cooperative research into VLSI manufacturing technology), and the vertically integrated structure of the Japanese electronics industry, which may allow production of semiconductors to be subsidized by the production of electronic goods containing semiconductors.

At present, the most substantial federal involvements with the industry are its funding of semiconductor research and development (R&D) and the U.S.-Japan Semiconductor Accord. The accord negotiated between the two countries, which is outlined below, is intended to reduce the market barriers in Japan for U.S. semiconductors and, by setting minimum prices, to eliminate the possibility of cross-subsidizing semiconductor production. The Sematech manufacturing consortium, which is supposed to bring U.S. manufacturing capabilities up to the level of those in Japan, is patterned after the VLSI project.

Federal Research and Development Programs

The debate over the possible federal role in Sematech may obscure the already substantial efforts of the federal government in semiconductor research. Federal agencies have been involved in the U.S. semiconductor industry since its inception and have contributed to its competitiveness. Furthermore, federal agencies spend far more on semiconductor R&D than does the government of Japan, although not all U.S. spending is related to commercial efforts.

Federal agencies will spend an estimated $400 million to $500 million in 1987 on research into semiconductor materials, design, and manufacture (see Appendix A for details). The largest amounts (over $300 million) are being spent by the Department of Defense. Most of their research, however, has only limited short-term commercial potential. The Department of Energy's National Laboratories also have research programs on semiconductor materials and processing, totaling almost $80 million. The National Science Foundation spends $30 million on semiconductor research, although most of its money is for basic research in such areas as the structure and characterization of materials. The National Bureau of Standards spends $5 million a year developing technology to measure semiconductors.

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[1] The Semiconductor Industry Association (SIA) has several publications on this theme. See, for example, *Semiconductors & U.S. Competitiveness* (Cupertino, Calif.: SIA, February 1987).

Although federal agencies already spend a great deal on what appears to be support of the semiconductor industry, most of this money is spent to develop military and other noncommercial uses of semiconductors rather than to further manufacturing technology. The largest amounts of funds are spent to develop radiation-hardened (rad-hard) integrated circuits, which are used solely in military or space applications, represent only a small fraction of semiconductor sales, and have only limited commercial potential.

The other major federal research effort involves the use of semiconductor materials other than silicon, most notably gallium arsenide. Although these materials may become increasingly important in the future and indeed may very well replace silicon as the preferred material for semiconductors, silicon will probably dominate the commercial market for the remainder of this century.2/ Thus much of the federal research dollar, while financing materials research with future applications, is spent acquiring knowledge of little immediate commercial relevance.

This last conclusion points to a gap in current federal funding of semiconductor R&D that in turn may not be covered by semiconductor firms or their suppliers of manufacturing equipment. Outside of radiation hardening, which is primarily for federal use, much federally funded semiconductor R&D is basic research that will become commercially important only in the next century. By contrast, semiconductor companies concentrate their manufacturing R&D on solving current problems or providing background for their next manufacturing facility. The middle range of R&D--falling somewhere

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2. James Meindl, "Future Needs of Ultra-Large Scale Integration," in Semiconductor Equipment and Materials Institute, *Forecast: The Business Outlook for the Semiconductor Equipment and Materials Industry, 1987-1989* (Mountain View, Calif.: SEMI, 1987), p. 2.

between the next factory and the next century--is thus often alleged to be missed by both federal agencies (and presumably their sponsored R&D at universities) and private firms.3/

The U.S.-Japan Semiconductor Accord

The semiconductor accord signed by Japan and the United States in the summer of 1986 represented a major departure of federal policy and a new level of federal involvement in the semiconductor industry. By forming a cartel comprising the world producers of semiconductor memory devices and guaranteeing U.S. producers of integrated circuits a minimum price, U.S. trade representatives hoped to improve the financial circumstances of the U.S. producers. This spring the U.S. government enforced cartel pricing by imposing duties on Japanese goods for selling at below-market prices in other countries. Subsequently, the Japanese Ministry of International Trade and Industry (MITI) put pressure on Japanese producers of semiconductors to reduce production of dynamic random access memories (DRAMs), and the Administration has now begun to reduce the tariffs.4/ Ironically, the resulting DRAM shortage is threatening to stifle the recovery of the semiconductor industry that began earlier this year. Thus, having spent two years pressuring the Administration for the accord, U.S. semiconductor producers now want the enforcement reduced.

Terms of the Accord. The complete terms of the semiconductor accord have never been made public. While much information is available, details about several of the provisions have not been clarified. The published version of the accord has two central provisions. First, Japanese producers of semiconductors must sell their memory chips at or above their average cost of production, or fair market value, as

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3. For this argument, see Deborah Shapely and Rustum Roy, *Lost at the Frontier: U.S. Science and Technology in Trouble* (Philadelphia: ISI Press, 1985).

4. DRAMs are the most widely used type of semiconductor device, accounting for between 8 percent and 10 percent of U.S. shipments of integrated circuits. For a more complete description, see Chapter II.

calculated by the U.S. Department of Commerce.5/ At present, however, the fair market values are only slightly higher than the U.S. market prices.6/ Second, Japanese consumers of semiconductors will increase the number of integrated circuits they buy from U.S. producers.

Implementation of the Accord. The implementation of the accord has been controversial from the beginning. The first calculations of the fair market values caused DRAM prices in the United States to quadruple overnight. Then disputes arose over pricing in third-country markets. MITI at first said it could not make Japanese semiconductor producers restrain their output. This lack of restraint caused a glut of DRAMs in Japan. Inevitably, some of these integrated circuits were exported to other countries for assembly into final products, and U.S. producers of electronic equipment found themselves hurt by foreign competitors who had access to "cheap" DRAMs. Only after the Administration threatened to impose trade restrictions was MITI able to persuade Japanese producers to reduce output. Despite MITI's efforts, the U.S. Administration imposed tariffs on $300 million worth of Japanese imports in retaliation for violations of the accord in third-country markets. Shipments by U.S. semiconductor firms are now increasing substantially, in part because Japanese firms reduced their production.7/

Sematech's Role

Sematech would marshal public and private resources in a collaborative effort to improve the manufacturing technology of the semiconductor industry. This focus would address both the industry's

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5. The Japanese semiconductor producers provide the information on production costs to the Department of Commerce, which then calculates their average cost. The specific formula for calculating the fair market value is often used as one of the conventional tests for "dumping"--selling below costs. The details of the Department of Commerce calculations have not been made public and have been a matter of contention.

6. Minoru Inaba, "Hear 256K DRAM FMV About $2.80," *Electronic News*, June 29, 1987, p. 24.

7. "Semiconductor Firms Re-crank Idle Capacity," *Electronic News*, August 10, 1987, p. 1.

concerns about losing its competitive lead to Japan and federal concerns over advancing the national interests. Industry concerns would be addressed because Sematech would concentrate on an area that many independent technical experts agree needs to be improved. Federal concerns would be promoted through support for an activity--research relevant to the commercial manufacture of semiconductors--that has high potential spillover benefits, and is not adequately addressed in current federal R&D programs.

The emphasis on manufacturing technology--both in the proposal for Sematech and within the semiconductor industry--results from the common perception that this technology will be changing substantially in the near future. The demand for more powerful integrated circuits causes semiconductor producers to seek more from their manufacturing processes and equipment. Trends in the semiconductor industry are described in the next chapter. The details of the proposed consortium are outlined in Chapter IV.

CHAPTER II

OVERVIEW OF THE SEMICONDUCTOR INDUSTRY

The interest in establishing Sematech stems primarily from the perception that the competitiveness of the U.S. semiconductor industry is in broad decline. While the value of the Sematech consortium is more related to the social benefits it will create than to the competitiveness of the U.S. industry per se, conditions in the U.S. industry must be understood if only to identify Sematech's potential effects.

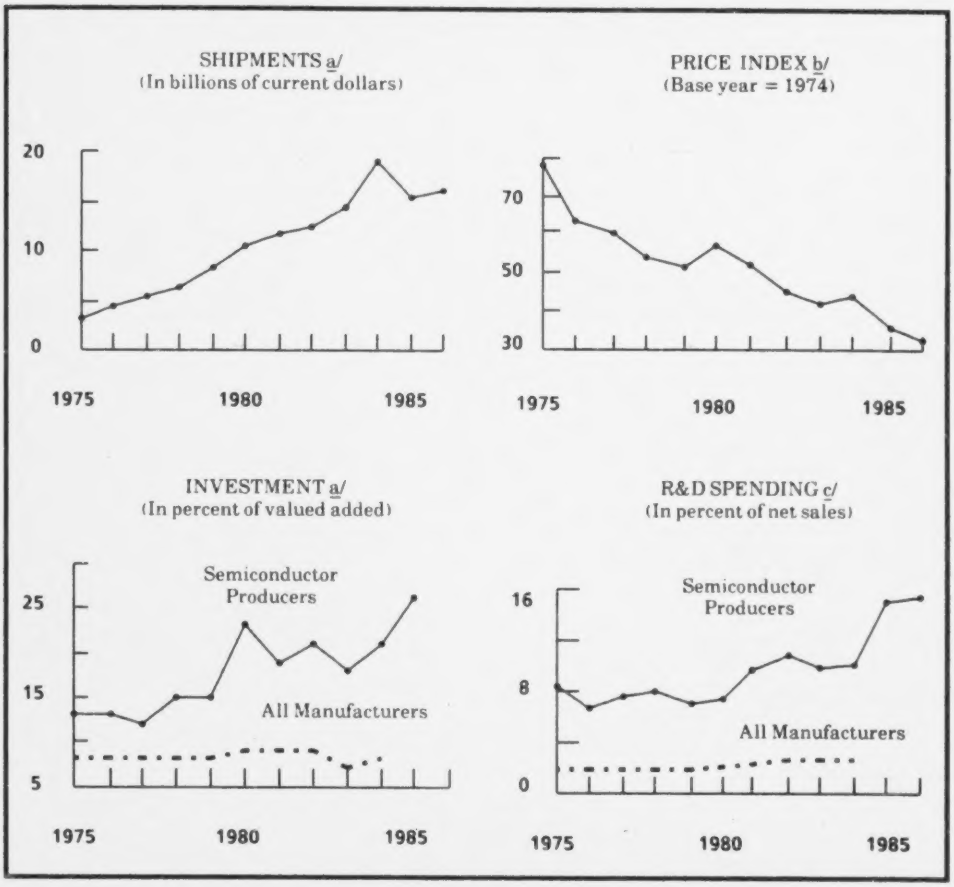
Although U.S. producers have largely been driven from the market for standard memory devices by foreign competitors, they retain their advantages in other devices used in manufacturing electronic goods. But U.S. firms have proved to be better at designing products than manufacturing them; the state of semiconductor manufacturing technology has been more widely recognized as a source of concern.

This chapter identifies important characteristics of the U.S. semiconductor industry--in particular, the portion of the industry that produces integrated circuits--and of the industry that manufactures equipment used in producing semiconductors. Appendix B presents a brief technical description of the range of products produced by the semiconductor industry and of semiconductor manufacturing technology. A glossary of technical terms appears at the front of this report.

THE U.S. SEMICONDUCTOR INDUSTRY

The U.S. semiconductor industry has grown quite dramatically since the early 1970s, as shown in Figure 1. In 1984, for example, shipments of semiconductors exceeded $19 billion. But this growth has not been steady. In 1981 and 1982, the rate of growth in semiconductor shipments slowed because the production of integrated

FIGURE 1. PERFORMANCE INDICATORS FOR U.S. PRODUCERS OF SEMICONDUCTORS



SHIPMENTS a/ (In billions of current dollars)

PRICE INDEX b/ (Base year = 1974)

INVESTMENT a/ (In percent of valued added)

R&D SPENDING c/ (In percent of net sales)

SOURCES: Congressional Budget Office using data from Department of Labor, Bureau of Labor Statistics; Department of Commerce, Bureau of the Census; Semiconductor Industry Association; and National Science Foundation.

a. Semiconductors defined as Standard Industrial Classification 3674. Data for the U.S. semiconductor industry include Japanese manufacturing facilities in the United States. There are relatively few of these facilities.

b. Price level of digital metal-oxide semiconductor (MOS) integrated circuits.

c. Semiconductor data for 1985 and 1986 are preliminary. The R&D data for the semiconductor industry come from the Semiconductor Industry Association (SIA). *Business Week* surveys of R&D suggest that the semiconductor industry R&D level (as a percent of sales) is lower than that reported by SIA (closer to three times its average of "all manufacturers"); see "R&D Scoreboard," *Business Week*, March 21, 1984. The data for "all manufacturers" are taken from National Science Foundation, *Research and Development in Industry, 1984* (Washington, D.C.: NSF, 1987, Table B-19).

circuits (which make up nearly 80 percent of the semiconductor market) by U.S. capital-affiliated firms stagnated.[1] The mid-1980s witnessed a temporary decline in semiconductor production as a result of lagging computer sales, although that now appears to have turned around and the industry is currently returning to economic health.

One indication of the advances made by this industry is the continual drop in semiconductor prices, also shown in Figure 1.[2] This price decline has two important implications. First, it indicates a significant increase in the productivity and competitiveness of semiconductor manufacturers, as they have managed continually to reduce production costs. Second, it implies an even greater growth in physical output than that shown by measuring only the dollar value of semiconductor shipments. As prices drop, more semiconductor units are produced per dollar.

The increase in shipments and drop in prices could not have occurred without substantial investments in both capital improvements and research. Figure 1 shows that the semiconductor industry has invested in both at a much higher rate than other manufacturing industries. The overall level of investment (as shown in Figure 2) accelerated in 1983--about the time that Japanese semiconductor firms began to penetrate the U.S. market. Although U.S. semiconductor firms have significantly increased their capital investments, they have still fallen behind Japanese producers. Capital expenditures by Japanese firms have grown steadily--from a level of about one-third that of the United States in 1979--and have now taken the lead. The European firms have not participated in the recent expansion of manufacturing capacity.

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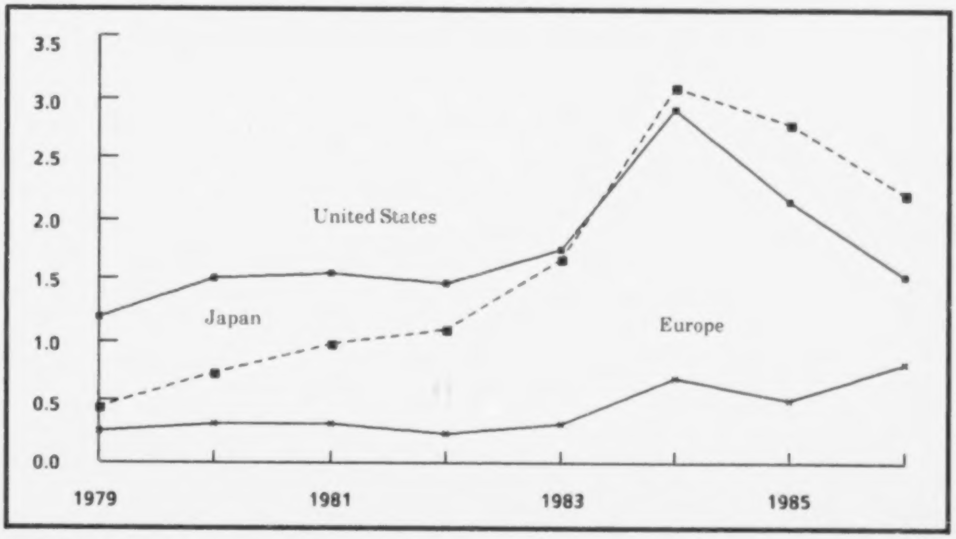
1. The definition of U.S., and foreign, capital-affiliated firms is an important one for understanding several issues raised later in this report. U.S. capital-affiliated firms are those that are predominantly owned by U.S. stockholders, regardless of where the firm's plants are located. Similiarly, foreign capital-affiliated firms are those owned by foreign stockholders, even if they operate plants in the United States.

2. Figure 1 shows the price decline of digital metal-oxide semiconductor (MOS) integrated circuits, which accounted for roughly half of U.S. semiconductor shipments in 1985.

FIGURE 2. CAPITAL EXPENDITURES BY SEMICONDUCTOR FIRMS IN THE UNITED STATES, JAPAN, AND EUROPE
(In billions of current dollars)



SOURCE: Integrated Circuit Engineering Corporation, Scottsdale, Arizona.

NOTE: Capital spending classified by country or region in which firm is based.

Structure of the Semiconductor Industry

Analysts commonly characterize the U.S. semiconductor industry as being composed of three types of manufacturers: **captive producers**, who produce only for internal consumption; **merchant producers**, who produce a broad range of semiconductor devices for the open market; and **niche producers**, who serve a specialized market with proprietary technology.

Captive producers manufacture between a quarter and a third of the total U.S. output.3/ International Business Machines (IBM), the largest U.S. manufacturer of semiconductors, accounts for between one-half and two-thirds of all semiconductors produced by captive

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3. The problems in valuation of captive production and the proprietary nature of output make firmer estimates impossible. Devices produced by captives often have no commercial equivalent. Furthermore, attributing the R&D for such devices and differentiating it from system design are difficult.

firms.4/ Other major captive producers include American Telephone and Telegraph (AT&T), Hewlett-Packard, General Motors (Delco), Digital Equipment Corporation, Honeywell, and others.

The merchant producers are largely independent of firms that produce the electronic equipment or systems that employ semiconductors. Most of them are especially vulnerable to fluctuations in demand for semiconductors because they do not have large internal markets to shelter them. Of the big U.S. merchant producers, only GE-RCA, Motorola, and Texas Instruments produce enough electronic equipment to absorb some of their excess semiconductor production. In contrast, captive producers will attempt to keep their own capacity fully utilized before they turn to outside producers, insofar as they are able.5/

Niche producers specialize in one or more small families of products. Depending on how markets are defined, these firms may account for as much as one-seventh of all semiconductors produced in the United States. Proprietary technology and unique products give these firms a competitive advantage.6/ As so-called niche markets grow, many of them are becoming attractive enough for larger companies to enter.

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4. See W. Edward Steinmueller, "Industry Structure and Government Policies in the U.S. and Japanese Integrated Circuit Industries" (Center for Economic Policy Research, Stanford University, December 1986), p. 25. See also Jack Beedle, "Semiconductor Industry Statistics, Analysis and Economic Trends--Past and Future," in Semiconductor Equipment and Materials Institute, *Forecast: The Business Outlook for the Semiconductor Equipment and Materials Industry, 1987-1989* (Mountain View, Calif: SEMI, 1987), p. 48.

5. Steinmueller reports that in 1985, while merchant production was undergoing its worst contraction of recent memory, the captive producers were actually increasing output. See Steinmueller, "Industry Structure and Government Policy," p. 35.

6. For instance, a handful of firms make special integrated circuits that allow personal computer manufacturers to make IBM-compatible computers at low cost by replacing many conventional integrated circuits with a few special ones. Given the potential cost savings here, the absolute efficiency required in the manufacturing of integrated circuits is not a consideration in this specialized market, whereas it drives market share in commodity memory markets. Bernard Cole, "Despite IBM's PS/2, the Outlook Is Bright for Clone-Chip Makers," *Electronics*, June 11, 1987, pp. 81-82.

Vertical integration (the entry of a firm into businesses that either supply it with resources or use its product) is not now the dominant form of business structure in the semiconductor industry. But this situation is changing; the first steps toward vertical integration of the merchant producers are now being taken through alliances between producers of semiconductors and electronic goods. This change is a logical progression from the semiconductor industry's early period of growth (pre-1980), which was characterized by the strong technological performance of independent firms, to the present, where the advantages of size and diversity have begun to play a more important role in business survival.7/

Competition With Japanese Firms

U.S. semiconductor manufacturing firms remain the world's dominant producers, although their lead is shrinking rapidly. In 1975, U.S. capital-affiliated firms produced three-quarters of all integrated circuits.8/ The export of semiconductors by Japanese firms to the United States increased sharply in the late 1970s when demand outstripped available U.S. supply. Japanese firms quickly became dominant in the sale of semiconductor memories, capturing a larger share of the U.S. market with each new generation of memory device. By 1986, the U.S. share had shrunk to 55 percent (see Figure 3).

During the same period, the market share of Japanese capital-affiliated firms rose from 15 percent to 40 percent. The Japanese growth came largely at the expense of U.S. merchant producers, whose market share fell from 60 percent to below 45 percent of semiconductor devices traded on the open market.9/ In the closely

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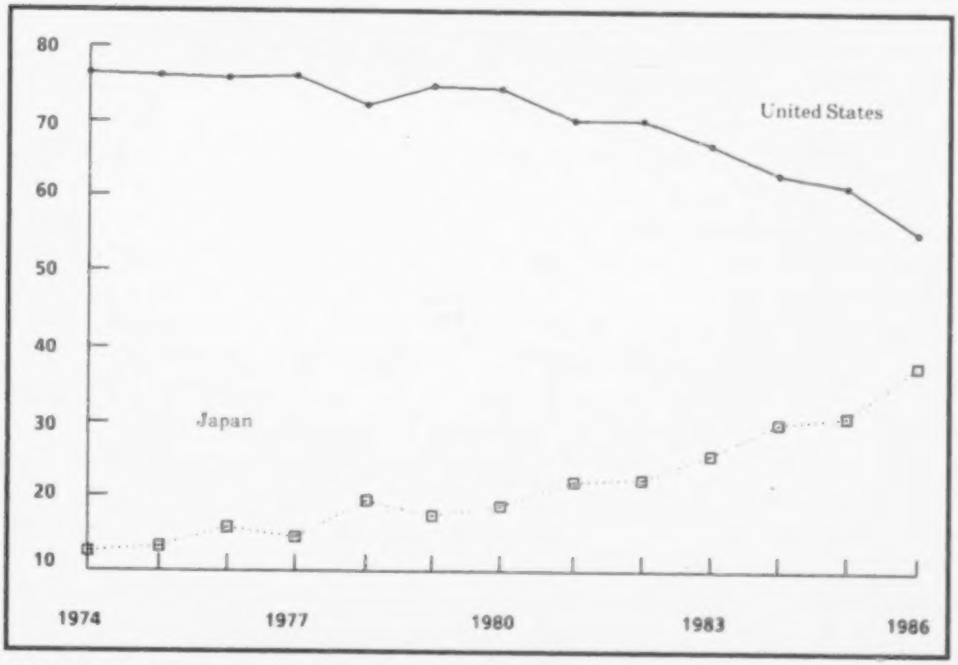
7. Steinmueller, "Industry Structure and Government Policies," pp. 32-42.

8. Exact estimates, while available, have a wide band of error associated with them. A significant percentage of total worldwide production is not traded but rather is consumed by the producing firms, which makes precise valuation impossible.

9. Department of Defense, Defense Science Board, *Report of the Defense Science Board Task Force on Defense Semiconductor Dependency* (February 1987), p. 5.

FIGURE 3. SHARE OF WORLD MARKET FOR INTEGRATED CIRCUITS HELD BY UNITED STATES AND JAPAN (In percents)



SOURCES: Dataquest Inc., San Jose, California; and Integrated Circuit Engineering Corporation, Scottsdale, Arizona.

NOTE: Includes both U.S. captive and merchant firms.

watched market for dynamic random access memories (DRAMs), the U.S. share has plunged even more, going from over three-quarters of open-market production in the mid-1970s to less than one-quarter in the mid-1980s, even though absolute production rose.10/

The growth of foreign producers of semiconductors--particularly those in Japan--coincided with a severe worldwide downturn in demand for semiconductors in 1985 and 1986. Because of the simultaneous occurrence of these two events, many analysts have blamed the decline in the U.S. share of the semiconductor market on Japanese expansion. However, roughly two-thirds of the decline in U.S. production can be attributed to the drop in global demand, and

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10. Ibid., p. 20.

only one-third of the decline resulted from increased production by Japanese and other non-U.S. firms. World production declined by 13.2 percent between 1984 and 1985, while U.S. production declined by 19.4 percent. Thus, even if every producer's share had remained constant, U.S. production would have dropped by 13.2 percent, or roughly two-thirds of its actual decline.11/

The semiconductor manufacturing industry in Japan is dominated by a dozen vertically integrated electronics firms to whom semiconductors represent a small fraction of sales, and who consume a large part of their output. Some analysts have argued that this arrangement allows Japanese firms to subsidize their semiconductor production with profits from consumer and other downstream (end-market) products.

Semiconductor Memories. Japanese producers employ a strategy of high-volume production to realize economies of scale, together with an emphasis on innovative processes. The production of DRAMs, for example, is generally more cost-efficient in Japanese than in American firms; American merchant producers appear to have ceded the DRAM market to the Japanese manufacturers.

Some U.S. industry observers now fear that Japan's domination of one generation of DRAMs will spread to the production of other devices at the cutting edge of semiconductor technology. Part of this concern relates to the critical role of DRAM production in the development and testing of semiconductor manufacturing methods.12/

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11. Estimates for U.S. producers are based on data from Department of Commerce, *U.S. Industrial Outlook, 1987* (1987), p. 32-3; estimates for non-U.S. producers are from Dataquest Inc., San Jose, California. The Department of Commerce data include some Japanese semiconductor production in the U.S. total (because of their U.S.-based production) and exclude U.S. semiconductor production in Japan and Germany. Using only Dataquest estimates would change the relative proportions but not the implication.

12. DRAMs have two qualities that make them desirable from a manufacturing perspective, where the manufacturer wants to achieve technological superiority. First, their design is simple; a 256K DRAM consists mainly of 256,000 repetitions of a single memory cell and the interconnections. Thus, these integrated circuits are akin to a test pattern that allow producers to see their results clearly. Second, DRAMs are produced by the million. The need to produce millions of devices allows semiconductor manufacturers to learn from their mistakes and increase their yields.

But the DRAM is not the only memory device that can be used for this purpose. Static random access memories (SRAMs) and erasable programmable read only memories (EPROMs) also have been used for testing, and many U.S. firms still produce these devices, despite competition from Japan. Moreover, U.S. captive producers still make high-volume memory chips--firms such as AT&T and IBM continue to supply their own needs, including 256K and 1-megabit DRAMs. At least one merchant (Texas Instruments) still makes DRAMs for the open market.

Competition from Korean producers of semiconductors is also affecting the world semiconductor memory markets. Korea now exports leading-edge semiconductor products to the United States and hopes to become a leading supplier of semiconductors. Korean producers have explicitly targeted the Japanese segment of the semiconductor memory market.13/ Like Korea, other newly industrializing countries will probably be willing to take short-term losses to enter the semiconductor memory market in the future.

Microprocessors. Although Japan has made dramatic gains in the production of DRAMs, U.S. firms continue to lead in many important areas of semiconductor technology. U.S. makers of microprocessors now have an almost insurmountable advantage in software--there are tens of millions of computers and other machines that run on the software developed for U.S.-produced microprocessors. New microprocessors, if they are to compete, must be able to run that existing base of software as well as provide new capabilities. Thus, unless Japanese microprocessor makers got so far ahead of U.S. companies as to "leapfrog" this technology--a highly unlikely occurrence--the U.S. advantage appears secure.

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13. For a discussion of the Korean semiconductor strategy, see Kim Chang-Kyong, "Out of the Laboratories and into the Factories," *Business Korea* (August 1984), pp. 27-35. See also Shelley Tsantes, "Lean, Mean and Hungry: Here Come the Koreans," *Electronic Business*, May 15, 1985, pp. 44-50.

The major challenge from Japan in the microprocessor market is in smaller, less expensive devices.14/ Japanese firms produce more 4-bit and 8-bit microprocessors than do U.S. firms; the United States, on the other hand, produces more 16-bit and 32-bit devices, which are newer and more expensive. When all four sizes of microprocessors are added together, Japan's physical output is greater, even though the output of U.S. firms has a higher dollar value.15/

Application-Specific Integrated Circuits (ASICs). The increasing sophistication of both the software that designs semiconductors and the integrated circuits themselves have made ASICs, which are designed for one narrow use, more attractive. Anxious to get out of commodity memory markets with their depressed profit margins, many U.S. producers have begun to produce ASICs. The rapid growth of ASIC markets--one estimate suggests that ASIC sales will quadruple by 1992--also attracts companies.16/ Despite the vaunted U.S. advantage in design, Japanese companies are also a major force in this area. One recent industry study suggested that three of the five largest ASIC producers, including the leading producer, are Japanese.17/ Part of their success derives from their long-standing concentration on custom design of integrated circuits for consumer products and electronic systems, which constitute a greater share of the Japanese market, as shown in Table 1. Although the initial designs were not particularly sophisticated, they gave the Japanese industry a solid foundation in this area. Now Japanese firms have begun to make substantial investments in design facilities in the United States to give them bases from which to work. The reputation

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14. Another challenge to U.S. dominance of the microprocessors market may come from the Nippon Electric Corporation's (NEC) attempt to manufacture a proprietary microprocessor completely compatible with the Intel 8086/8088 microprocessor used in IBM-compatible personal computers. The NEC V series can run all the same software and at a faster rate than the Intel devices it replaces. NEC's design, however, may have constituted a copyright infringement. The U.S. courts are now deciding this case. For a short history of the case and trials, see the June 1986 issues of *Electronic News*.

15. Shelley Tsantes, "Microprocessors: Who Buys What and Why," *Electronic Business*, October 15, 1986, pp. 90-93.

16. Stan Runyon, "The Great ASIC Wave Gathers Force," *Electronics*, August 6, 1987, pp. 58-59. See also Steinmueller, "Industry Structure and Government Policies," p. 50.

17. "ASIC Top Ten," *Integrated Circuit Engineering News* (June 1987).

TABLE 1. END-USE MARKETS FOR INTEGRATED CIRCUITS, BY REGION (In percent of 1986 total consumption)

	All Regions	U.S.	Japan	Europe	Other
Military	7	15	0	5	0
Industrial	13	12	10	18	13
Telephone	19	18	18	27	14
Consumer	29	15	39	30	53
Computer	32	40	33	20	20
Total	100	100	100	100	100

SOURCE: "Where Do the ICs Go?" *Integrated Circuit Engineering News* (March 1987).

NOTE: Consumer includes automotive use. Computer includes data communication.

of Japanese firms for service has also helped them in this market, as ASICs are very service-intensive.

Electronic Goods. The U.S. domination of sophisticated electronic equipment also eroded in the 1980s, as seen in Figure 4.18/ The deterioration may have had more to do with the budget deficit and the value of the dollar than with any technological decline. But foreign producers, having made substantial inroads, are not likely to allow U.S. firms to regain their former market shares without vigorous competition, and will be drawn to invest in semiconductor manufacturing technology to reap the economic benefits of vertical integration. In fact, the loss by the United States of its share in the world semiconductor market to date has followed its decline as a supplier of electronic goods. As Japanese, Korean, and other firms have begun to supply more electronic equipment, they have used their own components, including semiconductors, to produce that equipment.

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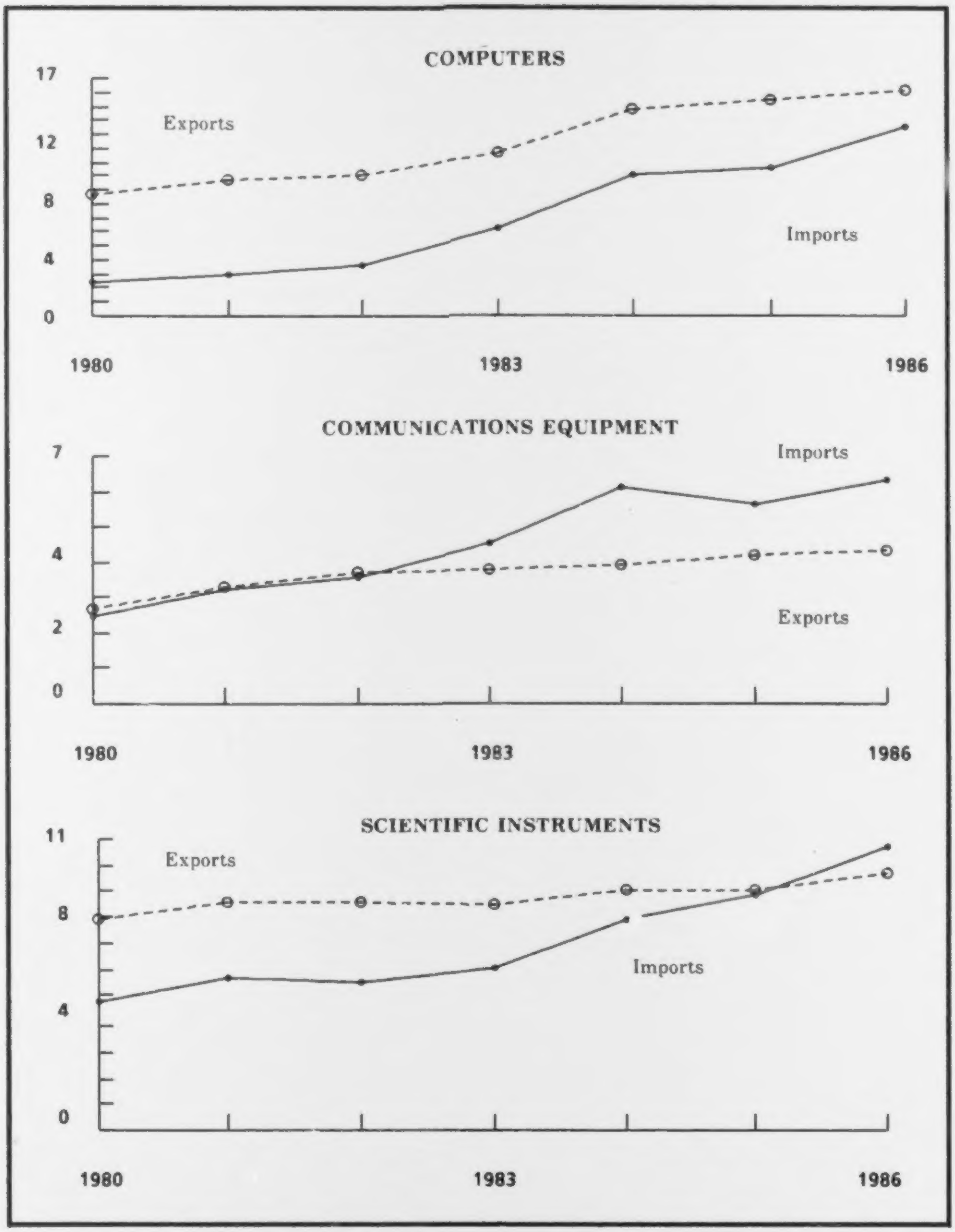
18. For more details, see Congressional Budget Office, *The GATT Negotiations and U.S. Trade Policy* (July 1987), Chapter III.

FIGURE 4. U.S. EXPORTS AND IMPORTS OF ELECTRONIC EQUIPMENT (In billions of current dollars)



SOURCE: Department of Commerce, Bureau of the Census.

NOTE: Computers includes all trade in Standard Industrial Classification (SIC) 357 Office and Computing Machines. Communications Equipment includes all trade in SIC 366 Communication Equipment. Scientific Instruments includes all trade in SIC 38 Instruments and Related Products.

THE U.S. SEMICONDUCTOR MANUFACTURING EQUIPMENT INDUSTRY

Like the U.S. semiconductor industry it serves, the U.S. semiconductor manufacturing equipment (SME) industry has been losing market share to its Japanese counterpart. Although producers in the United States still dominate in many areas of manufacturing, several panels of experts have sounded alarms regarding future technological trends.

Industry experts estimate total 1985 worldwide sales of semiconductor manufacturing equipment to have been in the range of $6.0 billion to $6.5 billion.19/ In 1986, sales dropped to roughly $5.0 billion as a result of the worldwide semiconductor recession. This decline was a substantial reversal; sales of semiconductor manufacturing equipment had been growing at an annual rate of over 25 percent since 1979.20/

In 1986, U.S. firms sold roughly $2.8 billion of the world total, while Japanese SME firms sold $1.7 billion. The U.S. share of worldwide SME sales--about 55 percent--corresponds roughly to the U.S. share of the semiconductor market and has been declining.21/

In 1986, equipment purchases by Japanese and U.S. manufacturers of semiconductors were each in the range of $2.2 billion. U.S. capital-affiliated companies produced over 80 percent of the equipment bought in the U.S. market, but only 30 percent of that bought in the Japanese market. However, the proportions were more than reversed for Japanese producers: they manufactured 60 percent of the equipment purchased in Japan but only 11 percent of U.S. purchases. In other countries, U.S. firms had almost 50 percent of the market, while Japanese firms had less than 25 percent.

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19. The estimates are largely taken from Jerry Hutcheson, "Front-End Wafer Fab Equipment Marketing Forecast," in Semiconductor Materials and Equipment Institute, *Forecast: The Business Outlook*, pp. 198-223.

20. Extrapolated from Department of Commerce, *A Competitive Assessment of the U.S. Semiconductor Manufacturing Equipment Industry* (March 1985), p. 31.

21. Department of Defense, *Report of the Defense Science Board Task Force on Semiconductor Dependency*, p. 5.

Structure of the U.S. Semiconductor Manufacturing Equipment Industry

The large size of the U.S. semiconductor industry allows producers of manufacturing equipment to specialize; many firms produce equipment for only one specific step in the highly exacting process of manufacturing semiconductors (described in Appendix B). About 700 companies produce manufacturing equipment, while many fewer companies produce the semiconductors themselves.22/ A few SME firms have substantial sales, but most have sales under $20 million. Most firms also have only one or a handful of products. As a result of this specialization, the top 14 companies account for only 55 percent of sales.23/

It is easy to enter the industry. Engineers from established companies regularly tap into venture capital funds to do so. Furthermore, the rapid growth in the complexity of semiconductor devices and the equipment that makes them has provided many openings for new entrants.

The Japanese SME industry, with about 500 firms, has a similar structure, although it is somewhat more concentrated than the U.S. SME industry--the top 11 SME firms in Japan account for 72 percent of sales.24/ There have been some major Japanese successes in this area, most notably the advances made by Nikon and Canon in lithography.

The State of U.S. Manufacturing Technology

Measuring the technological competitiveness of an industry (particularly one composed of many small, specialized producers) is far

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22. The Semiconductor Industry Association (SIA), the U.S. trade association, has 60 members but represents only part of the industry. One study suggested that 113 new semiconductor firms were started since 1977. Of course, many may have failed in the recent industry downturn. See Michael Malone, "America's New-Wave Chip Firms," *Wall Street Journal*, May 27, 1987.

23. Department of Commerce, *A Competitive Assessment*, p. 52.

24. Ibid., p. 53.

from exact. Several recent studies, however, have suggested that the Japanese semiconductor manufacturing technology is superior to U.S. technology and is advancing rapidly. The most detailed of these studies was done by a panel of experts assembled by the National Research Council (NRC), the operating arm of the National Academy of Sciences.25/ According to the NRC panel, the United States held the lead in three established areas of semiconductor manufacturing technology, but lost control of one major area (lithography) in the last year. Of greatest concern to the panel, however, were seven emerging technological areas in which Japanese firms were believed to be leading. Thus, while the United States is currently ahead, the NRC panel suggested that Japan seems to be gaining in these areas.

Some people have argued that the quality of Japanese manufacturing equipment is not necessarily the cause of either the greater competitiveness of Japanese semiconductor producers or the current weakness in U.S. semiconductor manufacturing. U.S. makers of semiconductors have access to most of the same manufacturing equipment as the Japanese firms, although some advanced testing equipment is not yet available in the United States. Although the Japanese investment rate has been higher than that of U.S. semiconductor producers, between 1980 and 1986 producers in both countries spent roughly the same amount on capital improvements.26/ Furthermore, U.S. producers probably have about the same number of new machines as do Japanese producers, even if the latter have a greater percentage of their capital stock invested in more modern technology.

The introduction by Japanese semiconductor producers of newer and more modern equipment, however, can quickly turn into a technological advantage. For example, one measure of the technical sophistication of equipment is the diameter of wafer used by a fabrica-

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25. National Research Council, Commission on Engineering and Technical Systems, Panel on Materials Science, *Advanced Processing of Electronic Materials in the United States and Japan* (Washington, D.C.: National Academy Press, 1986).

26. Integrated Circuit Engineering Corporation, Scottsdale, Arizona.

tion line. Semiconductor manufacturing equipment typically works most economically when using the largest wafer available.27/ Most new wafer fabrication lines are 6-inch (150-millimeter) lines. Fabrication lines using 4-inch wafers are at least two generations behind--in the United States, three-quarters of all wafer fabrication lines are 4 inches or less. By contrast, in Japan, only 40 percent are that size.28/

Japanese companies also seem to make better use of the equipment they have than do U.S. companies. This belief is held by many equipment manufacturers and semiconductor producers in the United States. Japanese companies often run their equipment three shifts a day: for two shifts the equipment is used in production; for the third shift, it is recalibrated and serviced. Comparable U.S. firms reportedly run similar machines until they need maintenance. Japanese semiconductor firms often add custom features to their machines and improve the materials-handling capabilities of the manufacturing equipment, presumably to fit into automated manufacturing strategies. Although U.S. semiconductor companies have a long history of making improvements in the capital equipment that is purchased from SME producers, they are nonetheless perceived by many people as lagging Japanese companies.29/

In the semiconductor industry, equipment use can affect output quantities very easily by increasing yields. Japanese manufacturers typically have been concerned with the acceptance rate of their

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27. Wafers with a larger surface area can accommodate a larger number of integrated circuits, which generally will lower the production costs. Some of the advantage of a larger surface area, however, is lessened by the concomitantly larger perimeter, which is where defects are likely to occur.

28. Beedle, "Semiconductor Industry Statistics," pp. 31-53.

29. See Eric Von Hippel, "The Dominant Role of the User in Semiconductor and Electronic Subassembly Process Innovation," *IEEE Transactions in Engineering Management* (May 24, 1977), pp. 60-71. For a more recent discussion, see Bruce Guile, "Investigation of a Transaction-Cost Approach to Market Failures in the Development and Diffusion of Manufacturing Technologies," presented to the Association for Public Policy Analysis and Management, Austin, Texas, October 1986.

output.30/ Their yields are therefore higher than those of their U.S. competitors, particularly for DRAMs. Higher yields lower the costs of products. Thus Japan's advantage in production technique may be more important than any advantage in production equipment.

Finally, Japanese firms are the leading providers of materials with which semiconductor devices are made. Six of the top ten semiconductor materials firms in 1986 were Japanese.31/ Japanese firms provided 92 percent of ceramic packages, 80 percent of the frames on which the actual semiconductor dies are mounted, and about 75 percent of the molding compound. Almost half the silicon wafers came from Japan.32/

CONCLUSIONS

The U.S. semiconductor industry's technological and market dominance is being threatened, partly by foreign competition, but more likely by internal weaknesses. Although Japanese producers now dominate the commercial DRAM market, their success has not yet led to large-scale penetration of other semiconductor markets traditionally held by U.S. companies; nor have they eliminated the production of DRAMs by U.S. captive firms.

Two trends, however, foreshadow problems for the U.S. semiconductor industry. First, the loss of market share by U.S. firms is likely to continue because other countries--like Korea--will probably begin large-scale production of semiconductors. Second, and more important, there is clear evidence of a weakness in manu- facturing techniques and possibly in equipment technology compared with

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30. William Finan and Annette LaMond, "Sustaining U.S. Competitiveness in Microelectronics: The Challenge to U.S. Policy," in Paul Krugman, ed., *Strategic Trade Policy and the New International Economics* (Cambridge, Mass.: MIT Press, 1986), p. 156.

31. "IC Equipment Makers Get Down to Business," *Electronic Business*, May 1, 1987, p. 84.

32. Daniel Rose, "Semiconductor Material Trends: Major Issues, Fab and Packaging Materials," in Semiconductor Equipment and Materials Institute, *Forecast: The Business Outlook*, pp. 31-53.

those used by Japanese producers. This weakness could easily translate into significant cost (hence price) advantages for Japanese semiconductor manufacturers. Other studies have provided analyses similar to this report, downplaying the importance of the DRAM market and emphasizing the weakness in U.S. semiconductor manufacturing practice.33/

On the other hand, many observers, both within and outside the semiconductor industry, have been more concerned about the loss of the merchant DRAM market and the slow pace of advances in equipment technology. A report of the Defense Science Board task force on semiconductors reflects this view. The report concluded that "...the current position of the overall U.S. merchant industry is...very tenuous in terms of present manufacturing capability."34/ The National Research Council report on manufacturing technology also presented a negative forecast. Yet the factors that encouraged Japanese firms to enter and then take over the DRAM market (for example, their mass-manufacturing skills) have not yet been shown to be applicable to other semiconductor devices.35/

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33. McKinsey & Co., a consulting firm, often takes this position. See Bob Neely and Mike Nevens, McKinsey & Co., "Politics Won't Cure the U.S. Chip Industry Woes," *Electronic Business*, November 15, 1986.

34. Department of Defense, *Report of the Defense Science Board Task Force on Defense Semiconductor Dependency*, p. 13.

35. National Defense University, Institute for National Strategic Studies, Mobilization Concepts Development Center, "Integrated Circuits: A Case Study of a Potential Foreign Source Dependency" (March 1987), unpublished mimeo.

CHAPTER III

THE SEMICONDUCTOR INDUSTRY AND THE PUBLIC INTEREST

Beyond the prospects for the future competitiveness of the U.S. semiconductor industry lies the more important issue of whether the competitiveness of that industry is an appropriate matter for public concern. Many of Sematech's proponents perceive the program as a response to a growing competitive disadvantage in international semiconductor trade. The benefits of Sematech, according to this view, are the output and employment associated with current and future semiconductor production that would otherwise be lost.

But while exceptions exist, the basic tenets of U.S. economic policy hold that shifts in the composition of the economy do not generally require government intervention. The rise and fall of individual industries, and the concomitant adjustments they require, may be caused by factors such as changing consumer tastes or technological advancement, as well as competition from imports. Thus, whatever the cause, the public policy role is typically limited to programs that help workers or communities adjust to economic change.

The roots of this policy of noninterference are found in economic theory. In the specific case of trade, if domestic production is displaced by imports, then the resources devoted to production of domestic goods will be freed for alternative uses. Through this process of displacement and adjustment, free international trade allows nations to specialize in producing goods and services according to their "comparative advantage" as evidenced by markets. This process, it is argued, ultimately will align the goods nations produce with their endowment of resources.

Yet this view of international trade has been challenged on several scores. Most notably, a growing majority of world trade is intra-industry trade--that is, trade in which nations with comparable levels of resources simultaneously import and export the same good. Thus, many analysts find it increasingly difficult to define comparative advantages among nations based on resource endowments, and often ascribe trade patterns to more broadly defined societal assets such as education, technology, culture, and government policies.1/

An exception to the principle of noninterference in the industry-level workings of the economy has traditionally been condoned when government intervention is needed to correct for so-called "market failures." Such failures occur, for example, when private economic actors correctly respond to market signals but the outcome is less than optimal from a societal perspective. A firm, for example, might produce and invest less than would be best for the economy as a whole if the benefits of its investments were usurped by other firms without compensation. Or, it might overproduce and overinvest if it were not required to pay the full social costs of its production, such as the costs of environmental degradation.

Given the traditional commitment to a policy of noninterference, the burden of proof is on proponents of government intervention--like Sematech's proponents--to demonstrate that market failures exist and warrant targeted economic policies. In essence, proponents must identify some type of public benefit associated with semiconductor production that accrues to the national economy, not just to individual semiconductor firms. Identifying these public benefits is somewhat subjective, but at least three types can be advanced: national security, research and development (R&D) results that benefit (or "spill over" to) the entire semiconductor industry, and spillovers to the economy as a whole.

NATIONAL SECURITY

The electronic content of U.S. weapons systems has been rising continuously throughout the last few decades; Computers and software accounted for about 2 percent of the cost of an F-4 Phantom in the 1960s, but for 25 percent of the cost of the next generation of military aircraft, the F-15. For the current generation, the F-18,

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1. For a short summary of intra-industry trade theory, see Paul Krugman, "New Theories of Trade Among Industrial Countries, " *American Economic Review* (May 1983), pp. 343-347. See also, Henry Kierzkowski, ed., *Monopolistic Competition and International Trade* (Oxford: Clarendon Press, 1984).

between 40 percent and 50 percent of all system costs are for electronic components.[2] In essence, U.S. military strategy has come to rely on electronic systems as the backbone of the U.S. strategy of having relatively few, but very sophisticated, weapons.

The Department of Defense's (DoD's) dependence on the U.S. electronics sector for its weapons systems is manifest in two interrelated ways. First, the DoD buys sophisticated electronics from domestic producers and wants to maintain a secure supply. Second, it relies on the industry to maintain the expertise needed to deliver state-of-the-art weapons systems. The semiconductor task force of the Defense Science Board (DSB), set up in 1986 to examine the impact of military dependency on foreign sources of semiconductors, reflected a concern about the second source of dependency as much as the first.

If the issue centered on maintaining a supply of semiconductors and eliminating constraints on foreign policy posed by dependence on foreign suppliers, the DoD could build semiconductor manufacturing plants dedicated solely to production for defense needs, or it could stockpile semiconductors (the military demand for imported semiconductors is only 0.1 percent of world output).[3] But these solutions would be more costly than Sematech.

More important, these solutions would ignore the interactions between maintaining a secure domestic supply of semiconductors and the ability of domestic suppliers to maintain technological expertise. Weapons contractors depend on a healthy commercial industry for such expertise. If the U.S. semiconductor industry were to deteriorate substantially, it is argued, U.S. firms would no longer be in a position to produce state-of-the-art or even current-generation chips for military uses. The Defense Department would lose the "know-how" embodied in the industry, and would find it more difficult to apply technology to defense needs. Thus, the ability to produce defense systems may deteriorate.

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[2] Dr. Arvid Larson, Statement on the Department of Defense FY 1987 Budget for R&D before the House Appropriations Committee, Subcommittee on Defense, April 29, 1986.

[3] Calculated from Department of Defense, Defense Science Board, *Report of the Defense Science Board Task Force on Defense Semiconductor Dependency* (February 1987), pp. 4 and 63.

The national security argument for Sematech, therefore, appears to rest more on concerns over losing a domestic technological base. Until now the Defense Department has assumed that the U.S. technological base was at the leading edge of semiconductor technology. The problem, for the military, was how to absorb and use the products generated from this base. The ability of the domestic semiconductor industry to compete with foreign producers allows the military to have access to state-of-the-art technology. For example, DoD was moved to oppose Fujitsu's bid to takeover Fairchild, probably not because of concern over security of supply, but because of concern over maintaining a domestic technological base. The military concern, therefore, is that this technological base can no longer be taken for granted.

SPILLOVERS WITHIN THE SEMICONDUCTOR INDUSTRY

One of the traditional arguments for public support of R&D is that the market, left to its own devices, will not invest in the "right" amount of R&D and will not make these investments in the "right" places. In research areas where it is hard for individual firms to capture all the benefits, such as basic and applied research, companies will have less incentive to invest than the good of society might suggest.4/ Thus markets may fail to deliver the right amount or composition of R&D.5/

The available evidence, at least among producers of semiconductor manufacturing equipment (SME), appears to conform to these theoretical expectations. The "know-how" that is developed by these producers can easily be transferred within the industry. Thus, unable to capture the full benefits of their research, firms spend less effort developing easily replicated improvements in technology. Foreign (Japanese) producers do not appear to succumb to this problem, partly because of efforts to perform this research on a collective basis.

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4. In other areas where there is substantial competition but firms are able to capture the bulk of the benefits (through product differentiation, for example), then firms might invest more than is socially necessary.

5. See Congressional Budget Office, *Federal Support for R&D and Innovation* (April 1984), pp. 10-17.

The focus of U.S. producers of semiconductor manufacturing equipment on short-term R&D gains has been suggested as a reason why they have fallen behind Japanese manufacturers, who have invested more heavily in long-term R&D (see Chapter II). In the National Research Council (NRC) report comparing U.S. and Japanese semiconductor manufacturing technology, the NRC panel found that "Japan's semiconductor industry is made up of at least ten entities that pursue long-range research and development on a scale matched by only a few U.S. companies."6/ The panel also noted that the Japanese industry and government are committed to pursuing R&D projects with lead times of 10 years. By contrast, most SME producers in the United States are small firms and cannot afford to wait 10 years for a return on their R&D investment, especially if a large share of the market will be captured by imitators, who copy the innovative product or process without compensating the original innovator.

Imitators that capture large parts or even the bulk of the market are a problem within the semiconductor industry itself. One study of semiconductor market share found that, depending on the type of device, innovators might not fare well at all. For evolutionary devices (such as the first 64K DRAM, which incrementally improved upon 16K DRAMs), the innovator of a new device lost the lead in market share in roughly two-thirds of the cases. For radically new devices, on the other hand, the innovator held the lead in market share in three-quarters of the cases.7/ This result suggests a pattern of overinvestment in radically new devices to hold market share and underinvestment in the commonplace improvements that allow for evolution of devices and manufacturing processes. The strengths and weaknesses (strong in design and weak in manufacturing technology) found among U.S. semiconductor firms suggest exactly this pattern.

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6. National Research Council, Commission on Engineering and Technical Systems, Panel on Materials Science, *Advanced Processing of Electronic Materials in the United States and Japan* (Washington, D.C.:National Academy Press, 1986), p. 32.

7. Francis C. Spital, "Gaining Market Share Advantage in the Semiconductor Industry by Lead Time in Innovation," in Richard S. Rosenbloom, ed., *Research on Technological Innovation, Management and Policy* (Greenwich, Conn.: JAP Press, 1983), pp. 147-173.

Sematech would concentrate on the manufacturing process--the area in which U.S. semiconductor producers devote the smallest share of their R&D effort. Industry sources suggest that U.S. producers spend no more than 10 percent to 15 percent of their R&D dollar on manufacturing technology. In the past, U.S. producers of semiconductors have devoted a great deal of resources to designing a product and to the initial manufacturing effort. Evidence suggests that once the product was fully launched, the resources were removed and yields stopped growing.[8] By focusing on manufacturing R&D, Sematech may alleviate the stagnation that is occurring after a product has been successfully introduced.

SPILLOVERS TO THE ECONOMY

Because the Sematech consortium would concentrate on manufacturing R&D, its developments should lower the costs of all semiconductor devices, not just those produced by Sematech members. Moreover, since semiconductors now have so many applications, these cost reductions should spread throughout the economy. If Sematech achieves its goals, the nation would benefit both from the better quality and lower cost of semiconductors the industry produces and from the incorporation of these devices in the products of other industries. An additional spillover benefit would be the development of the scientific and engineering personnel working on these projects.

Two analyses have suggested that the social benefits derived from recent technological advances are vastly larger than the private benefits to such activities and give credence to the traditional argument that R&D in technology promotes greater societal returns than just those that can be captured by private recipients. Even though these analyses measure the benefits of innovations in the computer industry, they are relevant here because semiconductors are

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8. In some sense, the behavior of semiconductor producers is consistent with the "satisfying" hypothesis--that is, once they hit a cost and productivity target, they cease trying to make further improvements. See Philip Webre, "Technological Progress and Productivity Growth in the U.S. Semiconductor Industry" (Ph.D. Dissertation, American University, 1983), pp. 139-140.

related to computers, and advances in computers are largely associated with advances in semiconductors.9/

One study found that the benefits of lower costs of computers in the financial services sector were larger than the computer expenditures of that sector by 1.5 to 2.0 orders of magnitude.10/ This result was derived by measuring the willingness of the adopting industry (financial services) to pay for the technological advances of the supplying industry (computers).

The other study found that the social rate of return on computer R&D varies between 50 percent and 70 percent, depending on assumptions of world market share and market structure. The rate of return to society is calculated based on the relationship between public and private investments in computer R&D, and the benefits of lower information-processing costs to consumers. Comparing the private and public rates of return, using the same assumptions, indicates that private rates of return are no more than roughly half as large as estimated public returns.11/ This differential implies that, in retrospect, the massive federal investment in support of computer R&D following World War II was indeed justified by the spillover benefits. This differential in the private and social benefits is consistent with other studies of industrial R&D investments, which find that, on average, the social rate of return is roughly twice the private rate.12/

This argument, however, is difficult to apply to any individual policy or R&D program. Even if, on average, the social rate of return

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9. Because semiconductors have other uses, these analyses may understate the full societal impact of semiconductor devices.

10. Timothy Bresnahan, "Measuring the Spillovers from Technical Advance: Mainframe Computers in Financial Services," *American Economic Review* (September 1986), p. 753.

11. In no case is the private rate of return larger than 55 percent of the equivalent social rate of return. Kenneth Flamm, *Targeting the Computer: Government Support and International Competition* (Washington, D.C.: Brookings Institution, 1987), p. 38.

12. See Edwin Mansfield and others, "Social and Private Rates of Return from Industrial Investment," *Quarterly Journal of Economics* (May 1977), pp. 221-240.

is twice the private rate of return, is it so for a given project? Furthermore, when does the government stop--how much federal support for R&D is enough? As outlined in Chapter I and Appendix A, the federal government is currently funding an estimated $400 million to $500 million of semiconductor research. This level is roughly one-sixth of the semiconductor R&D being done in the entire economy, although it is more like one-fifth of the R&D being done by semiconductor producers--the rest being done by producers of semiconductor manufacturing equipment.

"Downstream" Applications

There is little to suggest that the social benefits of future semiconductor R&D will be substantially less than those attributable to previous research. Technological advances since the early 1970s have made it possible to squeeze ever-larger numbers of circuits onto a single chip. This ability has had the effect of blurring the distinction between semiconductor components and systems. For example, the advanced microprocessor is virtually a tiny computer on a chip. As integrated circuit design shades into system design, innovation in semiconductor technology becomes directly intertwined with innovation and development in end-use industries. The future direction of semiconductor innovation with ever-smaller devices suggests that greater electronic capability will become available for more and more uses.

The semiconductor is probably an epochal invention; the future of manufacturing technology increasingly depends on semiconductor-based applications. From the conceptualization phase with computer-aided design, through the manufacturing phase with computer-integrated manufacturing processes, all aspects of production are premised on having integrated circuits that are more complex and powerful yet cheaper than exist today. Many of the dependencies are obvious: for example, without semiconductors there would be no robots. In other cases, the ties are less apparent: for instance, the increased use of "statistical" control of the manufacturing process depends entirely on the rapid absorption, transmission, and analysis of information on production lines. More rugged versions of the personal computer are being introduced on factory floors for controlling the manufacturing process. Semiconductors are at the heart of all this information technology.

Because the R&D performed in the semiconductor industry will spread to all other U.S. industries, federally funded semiconductor R&D can be viewed as a way of supporting R&D for industry as a whole. The benefits from semiconductor R&D will help other industries be more productive.[13] For example, semiconductors have allowed electronic components in manufacturing equipment to replace mechanical functions. These replacements typically have reduced the number of working parts and have increased the speed and reliability of the equipment, thus leading to measurable productivity gains. In addition, flexible manufacturing systems depend on electronic computers and other equipment that can be reprogrammed easily while maintaining precision. These systems typically operate faster and more reliably than the systems they replace, often producing outputs of higher quality. They also reduce the "down time" needed for making product or style changes, thus allowing quicker and less costly response to changing market conditions.

Although at some point these advances will slow down, few analysts believe that that will happen soon.[14] For example, the rate at which the costs of components declined began to accelerate in the late 1970s and has continued through the 1980s.[15] But the dwindling number of merchant producers threatens to hasten the decline of the rate of innovation in this industry. The merchants and niche producers have been faster to introduce new designs than have the captive producers, partly because of differences in motivations and market strategies. As noted in the previous chapter, the merchant sector has been especially hard hit by Japanese expansion and tendencies in the industry toward vertical integration. Sematech is explicitly intended to strengthen the merchant manufacturing technology base, thus strengthening the most innovative sector of the industry.

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13. For discussions of upstream and downstream R&D, see Congressional Budget Office, *Federal Support for R&D and Innovation*, pp. 37-47. See also Fumio Kodama, "Technological Diversification of Japanese Industry," *Science* (July 18, 1986), pp. 291-296.

14. Richard Levin, "R&D Productivity in the Semiconductor Industry: Is a Slowdown Imminent," in Herbert Fusfeld and Richard Langlois, eds., *Understanding R&D Productivity* (New York: Pergamon Press, 1982), pp. 37-54.

15. See Flamm, *Targeting the Computer*, pp. 21-32.

Development of the Science Infrastructure

The manufacture of high-technology products such as semiconductors creates opportunities for the advancement of scientific knowledge. It provides scientists and engineers with new problems derived from the application of previous knowledge to practical situations. This process of "learning by doing" builds up a productive asset, human capital. Just as the products of semiconductor research can spread to other industries, the knowledge and experience gained by the scientists and engineers conducting the research can also be diffused elsewhere in the economy.

As scientists and engineers change projects and work in new areas, they bring with them the experiences of past learning, be it through formal education or practical training. But, as in other areas of research, no firm has as much incentive as does society to provide scientists and engineers with additional, post-formal education. Because of the propensity of firms to underinvest in the creation of human capital, industries where such growth occurs naturally are said to be worthy of note, and federally funded research that helps create that human capital can have important societal benefits.

There is a precedent for the role of high-technology industries as institutional repositories of the stock of human capital. The Bell Laboratories were an attempt by the Congress to use the regulatory process to build the industrial stock of human capital. The American Telephone and Telegraph (AT&T) company was guaranteed a rate of return on every dollar invested in Bell Laboratories. Consequently, the Bell Laboratories were built up for decades as the premier U.S. industrial laboratory and a major source of innovation for the economy. The breakup of AT&T ended that federal effort to build and preserve the industrial science base without providing a replacement.

CONCLUSIONS

The above measures of federal interest are hard to quantify or to put into practice. Most industries make some unique contribution to the nation, and no measure allows analysts to rank the value of each contribution. This lack of a precise measure, however, does not obscure the existing good reason to believe that the market, left to its own devices, will fail to allocate the socially appropriate level of resources to many activities within the U.S. semiconductor industry.

This said, there remains a further set of questions concerning the cost of obtaining the benefits of competitiveness in semiconductor manufacturing.

Support for Sematech will cost the federal government roughly $100 million per year. But the U.S. semiconductor industry is returning to profitability, and there are many competing demands on the federal budget. Consequently, one must ask whether the public benefits of this industry are so great as to be worth the resulting increase in the federal deficit. Again, no readily available measure exists for comparing the benefits of reducing the deficit with the benefits of funding Sematech. However, the U.S. semiconductor industry may provide as good a case as can be made that the public benefits and spillovers resulting from the development of one industry justify federal financial support.

CHAPTER IV

EVALUATION OF THE SEMATECH PROPOSAL

Over the course of the last two years, support for an industrywide consortium to improve U.S. semiconductor manufacturing technology has grown. This idea was promoted both by the Defense Science Board (DSB) and by a task force of Semiconductor Industry Association (SIA) members.[1] The industry is in the process of forming such a consortium, called Sematech, and has asked the federal government to participate and match funds provided by private members. The Congress must now decide whether to join the consortium and on what terms. This chapter describes the proposed consortium and examines the benefits and risks of the Sematech proposal.

PLANS FOR SEMATECH

Sematech would be a six-year, $1.5 billion effort carried out in three phases.[2] As now envisioned, the intent of the consortium is to improve U.S. manufacturing technology in the areas of equipment, materials, and process. A planned production line would prove and integrate the technology, but actual full-scale manufacturing would be left to individual companies.

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[1] See Department of Defense, Defense Science Board, *Report of the Defense Science Board Task Force on Defense Semiconductor Dependency* (February 1987), p. 84. This report also made a series of subsidiary recommendations including establishing eight university centers for excellence in semiconductor science, doubling Department of Defense semiconductor R&D by refocusing current research efforts, increasing Department of Defense funding of semiconductor industry discretionary R&D, and forming a semiconductor advisory group. Depending on their configuration, several of these options may not cost the government substantial additional funds and so have not been analyzed here.

[2] Sematech itself may go on longer, but current plans call for federal funding for six years only.

The proposed budget for Sematech would require commitments of roughly $250 million a year for the next six years (see Table 2). Funding would come from three sources: member firms, the federal government, and the state and local governments representing the site selected for the Sematech facility. Private membership is limited to U.S. capital-affiliated semiconductor companies and suppliers of semiconductor manufacturing equipment (SME), who can join through their trade association. Annual dues for semiconductor firms are 1 percent of semiconductor sales, whether to a market or to other divisions of the same company, with the proviso that no more than 15 percent of total funding can come from any one private source. This cap is designed to ensure that no one company can dominate the consortium.

The federal government's contribution to Sematech would be annual outlays of $100 million for six years, starting in fiscal year 1988. Additional funding is expected from the state and local governments in whose jurisdiction Sematech is located. Proposals from groups interested in providing a site for the Sematech plant are now being considered by Sematech's site-selection committee. A group of engineering schools in New York State, for example, has

TABLE 2. PROPOSED BUDGET FOR SEMATECH
(By fiscal year, in millions of dollars)

	1988	1989	1990	1991	1992	1993
Labor Costs	23.1	50.0	60.7	67.2	71.0	74.6
Operating Expenses	18.0	33.8	41.1	45.2	46.6	46.9
Contracts	34.4	39.3	42.8	49.5	50.8	51.4
Capital Expenses	112.4	59.4	69.3	76.7	72.2	71.9
Facility Acquisition	40.0	44.2	0.0	0.0	0.0	0.0
Facility Upgrade	16.6	9.1	9.1	9.1	9.1	9.1
Total	244.4	235.8	223.0	247.7	249.7	253.9

SOURCE: Semiconductor Research Corporation, Research Triangle Park, North Carolina.

already offered Sematech a complex of facilities and an additional $40 million in incentives. In August 1987, the committee narrowed the list of possible sites from 13 to 6. Sematech will probably receive its state and local funding as soon as a site has been announced.

Sematech has three missions.3/ The first is to conduct research on advanced semiconductor manufacturing techniques. This R&D effort will be directed by the Semiconductor Research Corporation (SRC), an existing semiconductor R&D cooperative associated with the SIA, and will examine all phases of semiconductor manufacturing, such as lithography and etching. SRC will coordinate this R&D with other members of the semiconductor community, including consortium members, suppliers of semiconductor manufacturing equipment, universities, and federal agencies.

The second mission is to test and demonstrate the resulting techniques on a production line. The production line would run full time (seven days a week, 24 hours a day) and integrate all the manufacturing systems developed in the first component. Third, Sematech would develop processes to adapt these proven techniques so that they can be applied to the manufacturing of a wide variety of microelectronic products. The research for all these steps will be performed both by Sematech staff and by other organizations working under contract.

The six-year program calls for three concurrent phases corresponding to three different levels of density of integrated circuits. The near-term focus is on improving current commercial manufacturing practices rather than bringing entirely new materials or technology to the industry. Thus Sematech will concentrate on silicon rather than exotic materials, and on optical lithography rather than X-ray lithography. In later phases, however, new technologies may be needed. Phase 1, which would run from the last half of 1987 through the first half of 1990, focuses on the development of manufacturing technology for integrated circuits with minimum

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3. This discussion is taken from a presentation on Sematech by Larry Sumney, President of the Semiconductor Research Corporation, to the Workshop on DOE National Laboratories and the Semiconductor Industry: Continuing the Joint Planning, at Sandia National Laboratory, Albuquerque, New Mexico, May 26, 1987.

feature size (commonly called geometries) of 0.8 micron.[4] (A micron is one-millionth of a meter.) Phase 2, which would begin shortly after Phase 1 and run through 1990, concentrates on geometries of 0.5 micron. Phase 3, which would begin in 1988 and would run through the first half of 1994, is intended to develop manufacturing technology for geometries of 0.35 micron.[5]

The companies that join Sematech do so in order to involve themselves in the forefront of research on manufacturing process, in the hope of incorporating this research into their own facilities. The technology developed by Sematech will go first to member firms. But as makers of semiconductor manufacturing equipment incorporate the results of this research into their products, the technology will eventually spread to all semiconductor manufacturing firms in the United States, then to firms abroad. The benefits to the member firms would be the head start on the use of the technology, not an absolute monopoly. Technology developed by Sematech would become available under license after a suitable period, with the proceeds being used to fund further research. Sematech planners propose that the federal government, like any other partner, be eligible for a royalty-free license of any resulting technology.

Plans for Sematech include a formal program to transfer the technology to its members. This program culminates with Sematech personnel providing on-site assistance to member firms in implementing the new technology. Long before this step, however, member firms would receive interim reports and technical communications from Sematech staff. The consortium also plans to provide suppliers of semiconductor manufacturing equipment who win Sematech contracts with technical findings to incorporate into their products. A 500-person staff is anticipated, and supplying that number of people should not be a constraint. The industry consortium

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4. Only leading-edge DRAMs have reached this level of minimum feature size, and these devices have not yet entered mass manufacture.

5. Sematech may choose in later phases to participate in the development of synchrotron-driven X-ray lithography. The Congress is now considering a proposal for the Departments of Energy and Defense to develop such technologies jointly.

is now trying to locate funds, a site, and a chief.6/ Industry sources report that Sematech has commitments to join from semiconductor producers representing 80 percent of U.S. production.7/

EVALUATING THE PROPOSAL

Despite the preliminary status of Sematech's planning, enough of the major elements--purpose, program, and funding--is known to evaluate their potential contribution. This section does so, focusing on the following questions:

- Does Sematech address the right problems in the U.S. semiconductor industry?
- Does Sematech address the industry's problems in a way that also pursues national interests? and
- What risks does Sematech pose?

Does Sematech Address the Industry's Problems?

As noted in Chapter II, the weakness of the semiconductor industry lies in manufacturing technology generally, rather than in the sophistication of U.S.-made devices. But most R&D now carried out by semiconductor companies is in device design, not manufacturing technology.

Industry sources suggest that of the $2.0 billion spent by semiconductor companies for research, between 10 percent and 15 percent (or $200 million to $300 million) is for manufacturing R&D. Makers of semiconductor manufacturing equipment spend another $500 million.8/ The focus in Sematech on generic manufacturing

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6. The SIA board is serving as a temporary Sematech Board, and the SRC staff is serving as temporary Sematech staff.

7. See Robert Henkel, "FYI," *Electronics*, August 6, 1987, p. 8.

8. Presentation on Sematech by Larry Sumney to the Workshop on DOE National Laboratories and the Semiconductor Industry, May 26, 1987.

equipment and technique would bring new resources to bear on an acknowledged weakness that current research efforts do not adequately address. The $250 million spent by Sematech would increase spending for research on commercial semiconductor manufacturing in the United States by about one-third--a sizable increase.[9]

Sematech has good prospects for developing new manufacturing technologies. Given the attention it commands among industry leaders and the industry's financial commitments to it, Sematech will probably secure a highly qualified staff, and its results will be incorporated rapidly into actual production. But while Sematech will probably improve U.S. semiconductor manufacturing technology and may keep the semiconductor industry from falling further behind, it probably will not be able to restore the U.S. share of the world market to the levels enjoyed in the 1970s for several reasons. First, the semiconductor producers in Japan have substantial R&D programs and will continue to improve their manufacturing technology. Second, part of the success of Japanese semiconductor firms has come as a result of the success of Japanese producers of electronic equipment, and Sematech is not likely to reverse these gains. Finally, new producers from other countries will enter the semiconductor market, further eroding future U.S. market share.

Does Sematech Address National Interests?

Sematech addresses the three areas of federal interest outlined in Chapter III--national security, spillovers within the industry, and spillovers to the economy--though not to the same degree. Its greatest potential benefits will most likely accrue to the semiconductor industry; the contribution to national security, however, is unlikely to be substantial in the near term.

Spillovers and Learning. The major federal interest in the semiconductor industry concerns spillovers from research, both in the industry itself and the economy in general. These interests are likely to be fulfilled in some manner. Because of Sematech's plans for involving producers of manufacturing equipment, the resulting technological advances will probably be incorporated into the next generation of such equipment, benefiting all semiconductor producers. Improved manufacturing technology could in turn lower the costs of making products that use semiconductors--such as computers, robotics, communications equipment, and other electronic equipment--and finally result in lower prices to consumers.

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[9] While some federal semiconductor R&D may be devoted to manufacturing technology, much of it--research on gallium arsenide manufacturing technology, for example--is commercially irrelevant in the short term.

Given the difference between societal and private benefits, as outlined in the previous chapter, the benefit to the United States as a whole could far outweigh either the federal or the private investment in Sematech R&D. Furthermore, the interest Sematech has already generated in the technical community indicates that the consortium is likely to stimulate the expected benefits to the scientific and engineering communities.

An important source of confidence in Sematech's prospects lies in its decision to concentrate on manufacturing technology. As discussed above, individual semiconductor firms do substantial amounts of research--far more than the national manufacturing average, even during periods of industrywide financial losses. But the bulk of this work concerns product design rather than manufacturing equipment or processes. Many economists believe that research on manufacturing process is underfunded, given its potential return to society.10/ The counterargument to this position, however, has generally been that one industry's process is another's product, and that improvements in product design in an input-supplying industry become improvements in process elsewhere.

This argument, however, is less persuasive in the semiconductor industry because of the disparate sizes of semiconductor firms and SME manufacturers. As noted above, U.S. SME firms are much smaller and compete against more firms than do their Japanese counterparts. Thus, the level of research in the SME industry may be out of balance with the level of research on the design of semiconductors.

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10. See, for example, Harvey Brooks and Bruce Guile, eds., *Technology and Global Industry: Companies and Nations in the World Economy* (Washington, D.C.: National Academy Press, 1987).

National Security. Improving semiconductor manufacturing technology may not reduce U.S. military dependence on foreign suppliers for specific devices. Nor can Sematech guarantee that U.S. producers of semiconductors will find filling U.S. military needs a profitable activity, especially given the bureaucratic and technological requirements that accompany defense contracts. Sematech may, however, increase the domestic availability of any given technology. Its greatest contribution to national security may lie in maintaining the vitality of the U.S. industrial base. Nonetheless, while any direct military benefits from Sematech would appear to be long-term and incidental, the lower costs resulting from improved manufacturing technology would benefit DoD as well as all other consumers of semiconductors.

What Are the Risks?

An effort such as Sematech inevitably poses a range of risks. One of these, of course, is the conventional scientific risk experienced in all such projects--that research will be fruitless. But this risk will be no greater for Sematech than for any other comparable research project. In particular, there is no reason to believe that it will experience greater risk on this score than would a project undertaken by one firm, rather than a consortium.

But Sematech's special characteristics raise a series of other issues, including:

- Whether Sematech's results would be disseminated to best national advantage;
- Whether Sematech's consortium design would become a precursor to a collusive arrangement;
- Whether Sematech would unduly centralize the nation's research agenda in semiconductors; and
- Whether both the private and public participants can succeed in the new institutional roles imagined for them in the Sematech proposal.

Dissemination of Results. Sematech's agenda is a promising one because it will investigate an area where the incentives to individual firms are limited but national gains could be great. Sematech's contribution, therefore, will be the greatest insofar as its results are quickly disseminated to domestic producers but still held within the national community.

The dissemination of Sematech's results to domestic producers is largely assured. The movement of engineers and scientists among firms and the general availability of new semiconductor manufacturing equipment should allow new manufacturing techniques to spread throughout the economy.

But the results of Sematech are also likely to spread abroad, thus defeating the purpose of the enterprise. To some extent this spread is inevitable, if less rapid, through the same media as domestic dissemination--personnel movements, research journals, word-of-mouth, equipment design, and the like. Foreign dissemination, moreover, can also take place through the activities of U.S. capital-affiliated firms that are members of the Sematech consortium. Specifically, the U.S. firms may use Sematech products and results in their foreign production sites; many such firms already operate production facilities in Japan, elsewhere in the Asian rim, and in other developing countries.11/

The fact that U.S. firms operate such facilities is not necessarily a loss for the U.S. economy. If some stages of production--such as low-wage assembly--relocate abroad while the engineering, skilled-production, scientific, and research work that accompanies it remains in the United States, then the gains imagined from Sematech may yet be obtained while still realizing lower production costs for many devices consumed here.12/ But production facilities inevitably incorporate advances in engineering and science, even if these functions remain in the firms' U.S. headquarters. In some nations, a transfer of technology may be a precondition for allowing foreign companies to locate a facility there. Thus, whether Sematech's

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11. Most semiconductor devices imported into the United States are manufactured by U.S. capital-affiliated firms, not foreign firms (Department of Commerce, *U.S. Industrial Outlook, 1987* (1987), p. 32-4.

12. Relocating production facilities, however, entails important adjustment costs for displaced U.S. workers.

products and advances will be sent abroad by U.S. firms is as much an issue as whether they will be appropriated by foreign ones.13/

The Prospects for Collusion. An industrywide arrangement such as Sematech raises the prospect of collusion among members of the consortium to restrain trade.14/ For example, not allowing nonmember firms to have access to the results could keep them from entering or expanding within the semiconductor industry. The existing plans for Sematech, however, would make research advances available to outside firms after a suitable period if a royalty is paid. Thus, Sematech members hope to gain a head start in familiarizing themselves with its research products rather than to achieve a long-term monopoly. Nonetheless, the conditions for dissemination of Sematech's research results are an important determinant of its effects on competition and are discussed in greater detail below.

An additional concern is that Sematech could become a springboard for collusive standard-setting by its member firms--for example, using a new generation of technological improvements to build semiconductors or manufacturing equipment with proprietary technology so as to make them incompatible with other, existing equipment. Standard-setting of this type is already a major advantage of the U.S. industry because of the near-ubiquitous need to be compatible with U.S. software. Yet attempts to redefine the standards of the industry could be self-defeating. In the 1960s, for example, the French government tried to enter the computer industry as a matter of national policy and promoted a "Plan Calcul" computer system that was not compatible with the then-dominant IBM

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13. To the extent that labor costs are higher in the United States than elsewhere, increases in the productivity of labor would lower U.S. manufacturing costs. Thus, the advantage to relocating abroad might diminish, and U.S. firms may expand their domestic production facilities instead.

14. Because the consortium plan has been modified to eliminate commercial production, proponents of Sematech argue that the consortium would be covered by the 1984 National Cooperative Research Act and thus would not need a special Congressional antitrust exemption. CBO's analysis does not discuss this act or its implications for Sematech.

design.[15] The effort was a catastrophic failure, and contemporary efforts to change standards might also fail.

Diversification of the Research Agenda. Sematech requires some measure of centralization in its research agenda. Through its collective efforts, semiconductor and SME producers will be agreeing on a common research program. The portfolio of projects selected will therefore be less diverse than if member firms had taken equivalent amounts of resources and established their own research agendas.

Centralization, of course, allows companies to avoid the waste of resources that occurs when individual research programs are duplicated. Moreover, it is unlikely that the member firms would ever individually devote the same level of resources to Sematech tasks, because of their inability to appropriate the full benefits of the research (as discussed in Chapter III). Thus, it is likely that Sematech will increase the absolute amount of research on SME technology, although some of this increase may be financed by firms doing less research on product design.[16]

Yet Sematech could "guess wrong" in selecting a research agenda and in so doing be leapfrogged by foreign producers or pursue a path that leads to a technological cul-de-sac. Comparable criticisms have been made of the federal program that directed the nation's commercial reactors toward light-water technology instead of such alternatives as the high-temperature gas reactor--a direction taken largely, it is claimed, because small-scale versions of the light-water technology were already used on U.S. submarines.

Sematech's immediate emphasis on commercial technologies raises a comparable prospect; "horizon" technologies such as the use of gallium arsenide or X-ray lithography are being deferred in

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[15] William James Adams and Christian Stouffaes, eds., *French Industrial Policy* (Washington, D.C.: Brookings Institution, 1986).

[16] Many economic studies suggest that increasing federal R&D spending in one area of research also raises private R&D in that area. See, for example, Kenneth Flamm, *Targeting the Computer: Government Support and International Competition* (Washington, D.C.: Brookings Institution, 1987), p. 184.

Sematech's plans. Other federal programs, however, fund research into activities that are not part of Sematech's research agenda.

Will the Institutional Arrangements Work? Sematech involves two relatively new institutional forms for U.S. economic policy--a research consortium of firms within an industry, and a public/private partnership with government a largely silent partner. Whether the groups involved can succeed in these new roles is unclear.

While the proposed consortium mimics the highly successful Japanese VLSI program, track records for similar U.S. consortia are short and mixed, depending on the criteria used. Many research and development ventures have been created since passage of the National Cooperative Research Act of 1984; 59 cooperatives have registered with the Department of Justice since January 1985.17/ They range from two-partner ventures focused on a single problem to corporations with many members and a long-range agenda.

Of these cooperatives, the experiences of the Microelectronics and Computer Technology Corporation (MCC) and the Semiconductor Research Corporation (SRC) are relevant to the proposed semiconductor consortium. While these two more modest joint efforts have proved successful, the industry has had a hard time cooperating in other major efforts. In 1981 and 1982, in response to the first major market gains by Japan, the U.S. semiconductor industry designed Operation Leapfrog with some of the same goals as Sematech. That effort foundered during the semiconductor boom of 1983-1984. This experience raises the question of whether Sematech will last in good times--for example, if U.S. producers are helped by a depreciation of the dollar--as well as bad.

A separate issue is whether any one company will have the incentive to send its best prospects--either labor or technology--to the consortium, or if Sematech will lack the discipline that a team organized by a single firm might have. The experience of the MCC suggests that a dynamic cooperative can hire researchers of better quality than can individual companies. The long-term focus of the

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17. Department of Commerce, Office of Productivity, Technology, and Innovation, "Cooperative R&D in Industrial Competitiveness" (unpublished mimeo, March 16, 1987).

research itself and the size of the research groups, not the product or process applications, attract researchers. MCC has been able to hire about 20 percent of its staff researchers from universities and government laboratories.18/

Industry consolidations, mergers, and divestitures can also threaten a cooperative's long-term planning and viability. MCC had three members withdraw in 1986; only two have been replaced. Three other members have given notice that they will withdraw at the end of 1987. Most of these withdrawals resulted from mergers or divestitures in the industry, not from dissatisfaction with the work of the cooperative.19/ The exodus of member firms could destabilize the cooperative, however. If new members are not found, either remaining members will have to increase their support of research projects or the research agenda will have to be scaled back. Even after these departures, however, MCC membership remains at 17 companies, or 6 members more than they started out with.

Some of these cooperatives already have made breakthroughs in research and have disseminated their findings. MCC began delivering results to its members in the spring of 1985--earlier than the members had expected--through informal technology transfers and in laboratory sessions or seminars to brief sponsors on current research.20/ Because MCC's work is proprietary, full details and evaluations of the information conveyed are not available. One indication of MCC's success, however, is that some member companies--having seen the quality of MCC's results--have joined other research programs. And, an MCC member recently released the first product incorporating MCC-developed technology, an advanced design system for integrated circuits. A schedule has been set up for delivering additional research results to member companies in the near future.21/

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18. Merton Peck, "Joint R&D: The Case of the Microelectronics and Computer Technology Corporation," *Research Policy* (October 1986), pp. 219-231.

19. Lloyd Schwartz, "MCC Chief Hits Myths' of Cooperation Lack," *Electronic News*, July 20, 1987, p. 22.

20. Dr. Grant Dove, Statement before the Technology Policy Task Force of the House Committee on Science, Space, and Technology, July 15, 1987.

21. J. Robert Linebeck, "It's Time for MCC to Fish or Cut Bait," *Electronics*, June 25, 1987, pp. 32-33. Also see companion articles for further details.

Another issue concerns the role of the federal government, which has had little experience with this type of cooperative arrangement. Although it funds applied research with commercial value through such agencies as the National Aeronautics and Space Administration, the National Institutes of Health, and the National Science Foundation's Engineering Research Centers, the government itself is the director of the research agenda in these situations (with industry in a consultative role), rather than a "silent partner" as it would be in Sematech. Moreover, the issue of the social benefits associated with an industry's competitiveness is not the rationale behind these other efforts. To succeed, Sematech will require an agenda that meets the industry's needs. The government's role in creating such an agenda in this case is a consultative one. Sematech's prospects will depend to a great extent on the willingness of the government to take a cooperative and, in many respects, passive role in the consortium, once Sematech's basic policies have been set.

POLICY DESIGN ISSUES

Many details of the Sematech proposal remain to be determined. Yet enough is known to identify issues raised by Sematech's design that are of broad policy concern. Three of these issues are discussed in this section:

- The relationship between the dissemination of the results and the benefits of the program;
- The precedent established by Sematech in trade and adjustment policy; and
- The choice of federal agency that will manage Sematech.

Royalty Policy

The royalties that Sematech demands to license the use of its research results will help determine the rate at which these results are disseminated. As discussed above, the national benefits resulting from Sematech are furthered when these results flow within the national economy but not outside it. One way to control dissemination would be to adopt a licensing policy that charges progressively higher prices, with the lowest price charged to U.S. nonmember firms with U.S. production locations, the middle price to U.S. firms seeking to apply results in foreign production locations, and the highest price (or outright prohibition) to foreign competitors. Restricting access of non-U.S. firms to Sematech's results, however, would contradict the principle of open trade in services that the United States seeks to incorporate into the General Agreement on Tariffs and Trade (GATT). Furthermore, it would be extremely difficult to prohibit either U.S. or foreign firms that used Sematech's techniques in their U.S. locations from transferring them to foreign sites. Similarly, SME manufacturers who incorporate Sematech's innovations into their equipment would have to be restrained from exporting that equipment under such a policy. But these exports provide SME firms with revenues that fund further research and development and, therefore, contribute greatly to the vitality of the industry. And, as discussed earlier, scientific findings inevitably spread to all users through a variety of avenues. Thus, a pricing scheme for royalties that differentiates among classes of users may offer the best prospect for managing the dissemination of Sematech's research results.

Relying on royalties to control dissemination, however, does not obviate the need to have a long-term policy in mind when addressing the issues created by the foreign production sites of U.S. firms or the U.S. production sites of foreign firms. Attempting to discourage foreign firms from locating in the United States would deny the economy employment and the on-the-job training of skilled workers and engineers that occurs at production facilities. The level of access these firms are given to Sematech's results therefore should be related to the value of these benefits. Yet it would be virtually impossible to enforce an arrangement allowing firms to use a technique in a U.S. plant but not a foreign one. The federal representatives to Sematech may want to seek some general agreement on this issue as part of a larger understanding regarding the government's participation in Sematech and its policies toward the semiconductor industry in general.

Protection

Federal participation in Sematech, which is aimed at improving the prospects of a specific group of industries, raises the issue of protection--the most common form of federal assistance to industry. A previous CBO report discussed the generally-perceived failure of protectionist measures such as tariffs and quotas in assisting the industries to which they were applied.[22] That analysis identified two concerns: that protection did not address the sources of cost disadvantages in U.S. industries, and that it did not provide firms in those industries with incentives to modernize. Sematech, in contrast, would address a specific source of cost disadvantage in U.S. production and, if it succeeds in introducing a new set of manufacturing technologies into the industry, should increase the incentives for firms to invest. It therefore has many of the characteristics of a viable alternative to trade restraints.

The problem posed by Sematech with regard to protection is not the program itself but the precedent that it would set in this area. The persuasive arguments for Sematech do not concern whether or not the semiconductor industry is competitive, but what benefits (beyond simple output and employment) would accrue to the economy as a whole by having a viable semiconductor industry. Yet if the Congress determines to fund Sematech, it may soon have to decide whether other industries willing to form consortia and to impose a tax on themselves to advance their technological abilities also deserve similar federal support. Many industries may, in fact, merit such treatment, given the often-observed and pervasive weakness in U.S. manufacturing technology.[23]

In many cases, promoting technology may be a better strategy than bearing the costs of adjustment in uncompetitive industries. This is not, however, an argument for making technology programs into a form of entitlement for uncompetitive industries (although the existence of tax credits for research and development is analogous to such an entitlement for profitable industries). Rather, this argument suggests that candidates for such programs be evaluated according to criteria like those used in this analysis and discussed in Chapter III.

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[22] Congressional Budget Office, *Has Trade Protection Revitalized Domestic Industries?* (November 1986).

[23] See, for example, Brooks and Guile, *Technology and Global Industry*.

The Choice of Program Manager

The federal role in the Sematech proposal is novel enough that it is not obvious where in the federal government it should be located. The House of Representatives has given most authority for Sematech to the Department of Defense for fiscal year 1988, although it also authorized the Department of Commerce to make grants to Sematech in the Trade and International Policy Reform Act of 1987 (H.R. 3). The Senate Armed Services Committee has reported a bill that would give Sematech a $100 million authorization through the Department of Defense for fiscal year 1988. Subsequently, the Senate included a provision in the Omnibus Trade and Competitiveness Act of 1987 (S.1420) that would establish an interagency coordinating committee to oversee federal participation in the program. A final version of these trade bills for vote by the House of Representatives and the Senate has not yet been agreed to in conference.

The Department of Defense, with a 40-year history of overseeing programs aimed at assisting semiconductor and computer technology, has the technical and operational expertise to handle a large program like Sematech. The fact that DoD's research arm, the Defense Advanced Research Projects Agency, supported the computer industry throughout the 1960s provides one reason for assuming that a stronger computer industry would benefit DoD as a consumer. Its Manufacturing Technology (ManTech) program assists firms in the defense industrial base in adopting advanced technologies. The Very-High-Speed Integrated Circuit (VHSIC) program is the latest of these programs. Appendix A details the approximately $300 million in semiconductor programs now managed by DoD. These programs reflect DoD's awareness of the role that a competitive industrial base plays in the nation's defense.

Most of these programs, however, have reflected DoD's intention to drive the technology of an emerging area in a direction more compatible with anticipated defense needs. This, rather than commercial success or a "response" to foreign challengers, was the intention of the VHSIC program.24/ This highly focused approach has been taken

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24. See National Research Council, Commission on Sociotechnical Systems, National Materials Advisory Board, *An Assessment of the Impact of the Department of Defense Very-High-Speed Integrated Circuit Program* (Washington, D.C.: National Academy Press, 1982).

with such technologies as the radiation hardening of chips (which allows them to survive nuclear war) and the use of gallium arsenide as a semiconducting material. Given this orientation, DoD has consistently managed these programs to achieve technological performance at the expense of cost. For example, high-speed gallium arsenide 16K SRAMs are planned as part of the Strategic Defense Initiative at a cost of $1,200 each in 1988; an existing fast commercial version is available for $20 or less.25/ It is not surprising that prototypes of new technological devices have these costs. But the purpose of Sematech is to develop cost-effective commercial technologies, not to pursue technologically demanding but commercially irrelevant directions.

A proposed alternative to DoD would be an interagency coordinating committee, chaired by the Department of Defense, and including the Department of Commerce, the Department of Energy and its National Laboratories, and the National Science Foundation. The committee would be advised by an Advisory Council on Federal Participation in Sematech that comprises industry, scientific, and defense representatives.

The advantage of such a committee is that it would bring together a wide range of interests within the federal government, allowing it to apply greater expertise and focus on broader, long-term interests. On the other hand, the committee would have to form itself rapidly to administer effectively the $100 million annual appropriation due Sematech. Moreover, current legislation pending in the Senate would give the committee a full-time staff of only seven people, forcing it to rely heavily on personnel who are detailed from the agencies represented on the committee. Given that there are few personnel available at the Department of Commerce to make decisions regarding a technological research agenda and that the work funded by the National Science Foundation is done by outside contractors, the bulk of these experts will come from the DoD and its attendant laboratories and from defense-related functions within the Department of Energy. This composition may lead to a defense-dominated view of the semiconductor industry in the committee's dealings with Sematech.

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25. Presentation by Fung-Sun Fei to the Main Workshop on DOE National Laboratories and the Semiconductor Industry: Continuing the Joint Planning, at Sandia National Laboratory, Albuquerque, New Mexico, May 27, 1987.

APPENDIXES

APPENDIX A

FEDERAL SPENDING ON SEMICONDUCTOR R&D

Federal agencies will spend $400 million to $500 million on research into semiconductor materials, design, and manufacture in fiscal year 1987 (see Table A-1). Most of this money, however, is used to develop military and other noncommercial applications rather than to further the development of manufacturing technology that would benefit the industry as a whole. The federal agencies that conduct or support semiconductor R&D include the Department of Defense (DoD), the National Laboratories (NL) of the Department of Energy (DOE), the National Science Foundation (NSF), and the National Bureau of Standards.

The largest federal effort is DoD's development of radiation-hardened (rad-hard) integrated circuits, which represent only about 3 percent of chip sales and have only limited commercial applications. The other major focus of federal research is the use of materials other than silicon, most notably gallium arsenide (GaAs).

DEPARTMENT OF DEFENSE

The Department of Defense has two categories of semiconductor programs: R&D programs conducted by the branches of the armed services, and programs associated with the Office of the Secretary of Defense. Each service branch has a substantial ongoing program of semiconductor research, focusing on its specific needs. The Office of the Secretary of Defense (OSD) also a high level of semiconductor research. The largest of these programs is the Very-High-Speed Integrated Circuit (VHSIC) program, which focuses on the insertion of sophisticated integrated circuits (ICs) into weapons bought by DoD. The Strategic Defense Initiative Organization (SDIO) funds the development of both silicon and GaAs technology. The Defense Advanced Research Projects Agency (DARPA) supports a wide variety of semiconductor design and production efforts. The Manufacturing

TABLE A-1. FEDERAL SPENDING FOR SEMICONDUCTOR RESEARCH IN FISCAL YEAR 1987

Agency	Outlays
Department of Defense	
Office of the Secretary of Defense	
Very-High-Speed Integrated Circuits	122
Strategic Defense Initiative Organization	60
Defense Advanced Research Projects Agency	16
Manufacturing Technology	14
Microwave and Millimeter-Wave Monolithic Integrated Circuits	10
Defense Nuclear Agency	7
Armed Services	
U.S. Air Force	60
U.S. Navy	28
U.S. Army	25
Independent Research and Development	a/
Department of Energy	
National Laboratories	
Sandia	55 b/
Lawrence Berkeley	4
Brookhaven	2
Other	2 c/
Photovoltaic Research	15
National Science Foundation	30
National Bureau of Standards	4
Subtotal	454
Incremental R&D Tax Credit	75 d/
Total	529

SOURCE: Congressional Budget Office.

a. Cannot be estimated; see text.

b. Excludes work performed at Sandia but reimbursed by the Department of Defense.

c. Includes Oak Ridge, Lawrence Livermore, Ames, and Argonne.

d. Average of 50 and 100. See text for details.

Technology program (ManTech) spends a small amount on semiconductor manufacturing. The Microwave and Millimeter-Wave Monolithic Integrated Circuits (MIMIC) program is similar to VHSIC, but concentrates instead on telemetry circuits made from gallium arsenide, a faster alternative to silicon. The Defense Nuclear Agency (DNA) focuses on the development of rad-hard chips for use in nuclear weapons. Finally, the DoD reimburses federal contractors for a portion of their research costs under the Independent Research and Development (IR&D) program. Some IR&D funding has been going into semiconductor work.

Office of the Secretary of Defense

The Very-High-Speed Integrated Circuit Program. The VHSIC program was established in the late 1970s, after DoD had little success in interesting semiconductor firms in designing and manufacturing integrated circuits for military use. Semiconductor makers felt that military devices lagged in technical sophistication and had stringent radiation, temperature, and other environmental requirements that made them too expensive for the commercial market. The limited commercial spinoffs discouraged semiconductor firms from producing the integrated circuits needed by military planners despite the unit profits such chips might bring.

The VHSIC program was designed to ensure that sophisticated integrated circuits would be built for military use and that the military would actually use them. Thus, the program has devoted little funding to developing generic semiconductor technology or to improving semiconductor production equipment.1/ In fiscal year 1987, for example, less than half of the $122 million VHSIC expects to spend will be spent on semiconductor technology. The program has developed software for designing integrated circuits at a cost of $14.5 million. Another $46.8 million is being spent on technology development of both ICs and their use in prototypes. In line with the desire to increase DoD's use of advanced semiconductors, a large part

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1. For instance, only a few million dollars was spent on photolithographic systems, and the original $5 million to develop a laser-powered wafer stepper was cut back to roughly $2 million. (Brian Santo, "New VHSIC Litho[graphic] Systems Readied for User Testing," *Electronic News*, March 9, 1987.)

of the funds has gone to systems development and insertion techniques. Some funds were spent on yield enhancement, but this effort tended to be applicable to specific devices and production lines.

VHSIC is in the process of winding down, after having achieved many of its goals. Under the program, the sophistication of chips designed for military use has grown--although not as rapidly as that of commercial chips--and the military has begun to design products and systems around these chips.

Strategic Defense Initiative Organization. The SDIO has two main research programs on semiconductor manufacturing in progress, totaling $61.3 million in fiscal year 1987. The major project, costing $41.5 million, consists of a series of GaAs pilot-production lines to build high-density devices for eventual use in a space-based real-time computer. The proposed devices, which are more complex than most commercially available GaAs devices, include a 16,000-bit static random access memory (SRAM) and some gate arrays. The program is proving the manufacturing technology by increasing the number of usable devices that emerge from the production lines. Other than supercomputers, civilian uses for such devices include heterojunction optoelectronics (light-driven computer interconnects). SDIO's other research project is on semiconductor manufacturing, costing $19.8 million in fiscal year 1987, which deals with radiation hardening of silicon. Unlike GaAs, silicon is very easily affected by radiation like that which exists in space or would be produced in nuclear war. Weapons based in space or intended for use in nuclear warfare therefore require rad-hard chips.

Defence Advanced Research Projects Agency. Current estimates suggest that DARPA will spend between $16 million and $17 million on research related to semiconductor manufacturing in fiscal year 1987. Much of the work they fund has both commercial and military applications. Universities perform 40 percent of this research.

One aspect of DARPA research that has had significant commercial payoff has been the modeling of silicon processes. Using a computer program developed at Stanford University, a semiconductor manufacturer can present the design of an integrated circuit, and the computer program will tell the manufacturer how to sequence the processing steps. The third and fourth editions of this program have been widely used in industry. DARPA is now turning the updating of this program over to the Semiconductor Research Corporation, an industry research consortium, and is focusing its attention on producing the same type of program for GaAs devices.

In addition, DARPA is funding research in advanced materials, including ceramics and metallurgy, and is also sponsoring research on advanced processing techniques using focused ion beams and lasers to enable semiconductor manufacturers to work on a small part of the device at a time.

Manufacturing Technology. DoD gives its contractors research funds to enhance their production technology. The Manufacturing Technology (ManTech) program is spending an estimated $14.3 million on semiconductor manufacturing technology in fiscal year 1987. Radiation-hardened devices account for $7.3 million; solid-state microwave systems for $4.6 million; and mercury-cadmium-telluride (HgCdTe) arrays for $2.4 million.2/

Microwave and Millimeter-Wave Monolithic Integrated Circuits. The MIMIC program focuses on producing microwave and millimeter-wave sensors for military systems, such as satellites, radars, and guided munitions. Current projections suggest that MIMIC will cost $10.3 million in fiscal year 1987 and over $500 million through 1992. The DoD accounts for a major share of the microwave and millimeter-wave integrated circuits. However, these devices are too expensive to incorporate widely into weapons systems. Because of the stringent frequency, radiation, and environmental requirements, MIMIC will primarily use gallium arsenide technology.

Defense Nuclear Agency. As the agency within DoD responsible for nuclear weapons, the DNA is charged with helping to ensure the survivability of the weapons systems the department purchases. Agency researchers study, for example, the effects of atomic blasts (electromagnetic pulse) on electronic components. DNA is projected to spend $6.6 million on semiconductor research, all of which is devoted to radiation hardening.

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2. HgCdTe is a semiconducting material, one of the so-called III-V compounds that have properties of interest to the military in specialized applications, but only limited near-term commercial use.

Armed Services

U.S. Air Force. Current projections suggest that in fiscal year 1987, the U.S. Air Force will spend $59.7 million on semiconductor research, including research on materials and devices. The largest single program ($16.8 million) is developing GaAs technology. The next largest program ($7.3 million) concentrates on electro-optics such as lasers, detectors, and optical computing. Other research efforts include $6.8 million for microwave circuitry; $6.4 million for developing silicon chips, including radiation hardening and three-dimensional work; and $6 million to enhance the yield of an advanced data/signal processor. In all, the manufacturing initiatives account for $15.1 million, slightly more than half of which is for silicon.

U.S. Navy. In fiscal year 1987, the Navy's semiconductor research will total an estimated $27.5 million, including research on materials and devices. Much of the research does not involve silicon, which is the mainstay of the commercial market. Of the total, research on materials and electronic structures for semiconductors accounts for $15.9 million. (In this context, the Navy is experimenting with superconducting solid-state devices.) The Navy is spending another $5.4 million on advanced analog devices, $4.5 million on radiation-hardened digital devices, and $1.1 million on solid-state infrared sensors. The rest of the money is being used for control components.

U. S. Army. The U.S. Army is spending $24.8 million in 1987 on semiconductor research. The work includes R&D on radiation hardening, substrates, and materials. The Army is also performing research on ultra-high-speed integration. Other R&D programs focus on reliability and on upgrading obsolete semiconductors.

Independent Research and Development

The IR&D program allows defense contractors to add an overhead charge of between 3.5 percent and 4.0 percent to their sales to the government. The overhead charge, usually in the form of negotiated reimbursement for costs incurred, is to be spent on projects with potential federal relevance. A portion of the $3.5 billion spent by DoD in reimbursing federal contractors under the IR&D program is being spent on semiconductor research. Some defense contractors, for example, may be using their IR&D funds to break into GaAs technology. Because of the structure of the IR&D program and the procedures for reimbursing firms for bid and proposal costs, it is impossible to tally the amount.[3]

DEPARTMENT OF ENERGY

The Department of Energy (DOE) will spend an estimated $77 million in fiscal year 1987 for research on semiconductor manufacturing technology. The National Laboratories will spend $62 million, mostly on radiation hardening ($55 million). Research on photovoltaic energy accounts for another $15 million.[4]

National Laboratories

The National Laboratories, with their highly qualified scientific personnel and specialized equipment, have a wide variety of projects of potential use to the semiconductor industry. Their largest efforts in semiconductor manufacturing, however, currently have few commercial applications because they concentrate on radiation-hardening semiconductors for space and weapons systems. In addition to the laboratories discussed below, others also have semiconductor research programs of varying commercial potential. This section discusses the largest programs.

Sandia. The National Laboratory at Sandia is spending an estimated $50 million on microelectronics processing and science in fiscal year 1987, with production of integrated circuits accounting for an additional $20 million. Between $15 million and $20 million of their research expenditures, however, is incurred on behalf of the military services, which reimburse them.

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[3] For further discussion of IR&D, see Congressional Research Service, "Defense-Related Independent Research and Development in Industry" (October 18, 1985).

[4] Some radiation hardening R&D for the Department of Defense is performed by the National Laboratories. The funding is accounted for in the DoD programs discussed above and so is not included in these totals.

Despite a concentration on radiation hardening, which accounts for two-thirds of its budget, some of Sandia's research may play a role in commercial manufacturing of semiconductors. For example, Sandia developed techniques for selectively depositing tungsten and refractory metals on chips. Sandia originally needed the technology to overcome some of the limitations of radiation hardening.5/ As commercial devices have become more complex, they have hit similar limitations. Sandia therefore sponsored conferences for the U.S. semiconductor industry as well as foreign companies to discuss the technology of depositing tungsten. This year International Business Machines (IBM) has taken over the conference, which suggests, if only implicitly, the commercial usefulness of the technology. It is not possible, however, for CBO to determine how much of Sandia's R&D expenditures produces commercially useful technology.

Lawrence Berkeley Laboratory (LBL). The LBL spends roughly $3.8 million on semiconductor research that could be transferred to the industry within three to five years.6/ The laboratory has several collaborative relationships with semiconductor manufacturing companies to improve their manufacturing process. LBL has the facilities and personnel to work in such areas as advanced materials (including gallium arsenide) and on semiconductor processing science (including ion implantation and plasma etching). Scientists at LBL have developed the world's brightest X-ray beam source, now installed on the Stanford Synchrotron Radiation Laboratory, which, like the National Synchrotron Light Source (NSLS) at Brookhaven, can be used for lithographic experiments. LBL also has several lines of packaging research as well as several national user facilities, which

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5. Sandia technicians could not heat the chips to very high temperatures once they laid down the insulating layers. (Devices are reheated to smooth out the surfaces. Devices that are made without the final heating thus have surfaces with peaks and valleys and steep cliffs.) Technicians at Sandia developed ways of raising selected valleys by depositing tungsten and other refractory metals. This method eliminated cliffs, which are often the site of metal fatigue and breaks that cause short circuits.

6. This estimate is derived by taking LBL's total operating budget of $155 million and apportioning part of it to semiconductor research in proportion to the number of semiconductor projects divided by the total number of projects. If semiconductor projects are especially costly or cheap, this estimate may be off.

operate like the NSLS (described below). Most prominent among these is the National Center for Electron Microscopy.[7]

The Lawrence Berkeley Laboratory is also the future site of the advanced light sources (ALS). Building on the success of the National Synchrotron Light Source at Brookhaven, DOE has committed roughly $145 million, including $100 million in construction costs, to build the next generation of synchrotron at LBL. (Fiscal year 1987 costs are estimated to be $3.5 million.) After its completion in 1992, the new synchrotron's annual operating budget should be in the range of $20 million to $25 million. The ALS beam is 1,000 times brighter and more coherent than that of the NSLS, and its frequency can be tuned. Scientists connected with the project liken the NSLS to a flashlight and the ALS to a laser. At present, one-third of ALS use is slated for industry.

Brookhaven. The Department of Energy is spending $20.9 million in fiscal year 1987 at Brookhaven. The operating budget of the National Synchrotron Light Source (NSLS), which is located at Brookhaven, accounts for $17.5 million, and the rest is for facilities and capital improvements. NSLS officials attribute roughly 10 percent to semiconductor research.[8] Industrial and academic researchers use either the polarized X-ray beam or the ultraviolet beam at the NSLS, which allows experimenters to examine surfaces very closely. Manufacturers or users of semiconductors who are working at the NSLS include IBM, American Telephone and Telegraph, General Electric, and Xerox. Oil companies also use the NSLS in their research. Brookhaven is reported to be oversubscribed.

Companies pay a fee for using the NSLS; the NSLS pays only for running the synchrotron itself. Experimenters build their own facilities to use the X-ray beam and pay their own staff. In addition, unfunded experiments deemed technically worthy are assigned to one or another of the private facilities. NSLS provides the beams to users

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7. For a more complete description of LBL semiconductor facilities, see Lawrence Berkeley Laboratory, Office for Planning and Development, *Semiconductor Research Capabilities at the Lawrence Berkeley Laboratory* (February 1987).

8. Using this percentage, an estimated $2.1 million is spent on semiconductor research. This estimate assumes that semiconductor research is, on average, as costly as other NSLS research.

at no cost on the condition that they publish their results. Proprietary researchers must pay a full-cost recovery charge of $384 per eight-hour shift.

Semiconductor manufacturers generally have a different use for the NSLS and synchrotrons than do other industries. In addition to examining surfaces, semiconductor makers may be able to use the X-ray beam in their manufacturing process. As integrated circuits become denser and more complicated, the size of the individual features shrinks. At feature sizes one-third the size of the latest generation of memory devices, X-rays may be needed as light sources for the photolithography phase in the semiconductor manufacturing process.

Brookhaven is a possible site for a new synchrotron light source for use in developing a commercial X-ray lithography machine. This proposal is now being discussed in the Congress, DOE, DoD, and the scientific community.

Other National Laboratories. The laboratory at Oak Ridge spends roughly $1.5 million on semiconductor research that involves direct collaboration with industry or that could be transferred to industry in three to five years. The research focuses on the Surface Modification and Characterization Center at Oak Ridge. The research in semiconductor processing includes laser-assisted deposition of chemical vapors, microwave plasma processing, direct ion beam deposition, and ion implantation for the production of buried insulating layers. Other projects at Oak Ridge may have useful applications to semiconductor manufacturing in the future. The general nature of these projects, however, makes it difficult to assess the usefulness of the research to any one industry.

The Lawrence Livermore National Laboratory is the site of significant research on the packaging of semiconductors. This work has been done over the last year using VHSIC and SDIO funds. The DOE has provided no special funds for semiconductor research at this facility. The research on packaging has focused on laser-assisted pantography. This process uses a computer-directed laser beam to locally induce chemical processes that either deposit, remove, or imbed desired chemicals on the silicon wafer to create circuits.9/ In one example of this procedure, the chip-to-board interconnects are chemically deposited down the edge of the IC die during the fabrication process, rather than attached afterward as is typically the case. The use of laser-assisted pantography allows chips to have very thin interconnects, which can be helpful in reducing the fraction of the die used for interconnection. Some specialized integrated circuits currently may have 150 or more individual interconnects.

The Ames and Argonne National Laboratories also have semiconductor research programs totaling $1 million a year.

Photovoltaic Research

The photovoltaic (PV) or solar cells, which power satellites, navigational buoys, and, increasingly, hand-held calculators, are actually semiconductor devices (diodes) that turn light into electricity. They are typically made of the same materials (silicon and gallium arsenide) as other semiconductor devices and often are made in the same general way as other discrete semiconductor devices, such as regular diodes or transistors. Thus, the DOE's effort to promote PV energy overlaps in several areas with commercial materials research. Such research will cost DOE $15 million in fiscal year 1987.

The Department of Energy's photovoltaic research might prove most helpful to commercial manufacturers of semiconductors by lowering the costs of materials. Photovoltaic cells use larger amounts of semiconductor materials than do other semiconductor devices.10/ Thus, DOE's research on photovoltaics has concentrated on producing large amounts of semiconductor-quality silicon cheaply and on simplifying the production of other semiconductor materials. One

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9. Lawrence Livermore National Laboratory, *Laser Pantography: 1986 Status Report for the Very High Speed Circuit Program* (Livermore, Calif.: LLNL, February 1987).

10. Photovoltaic cells need to be larger than other devices because ultimately they are converting the sunlight that strikes them into electricity. The size of an object determines the amount of sunlight that strikes it; that is, a two-square-inch solar cell will receive twice as much sunlight as the one-inch solar cell next to it.

silicon manufacturing plant using technology developed in this program has already been built, and two more are planned or under construction.11/

One area of special interest is gallium arsenide on silicon (GaAs on Si) devices. This technology, in which a layer of GaAs is deposited on top of silicon substrate, promises to develop solar cells that can convert up to 30 percent of the energy they receive from the sun into electricity. (Conventional solar cells convert anywhere from 7 percent to 15 percent.)

The DOE's photovoltaic program is sponsoring research aimed at developing ways of manufacturing GaAs on Si, which is difficult. Conventional semiconductor manufacturing firms might gain from this technology. Working with silicon is at this point straightforward; large ingots of silicon can be grown, the silicon has mechanical strength, and it forms insulating oxides easily. However, silicon devices are slow, are difficult to use in lasers and light-emitting diodes (which are at the heart of fiberoptics), and operate only within limited temperature ranges. GaAs is the perfect complement to silicon. It is fast, can be made to emit light, and will operate at higher temperatures. Unfortunately, it lacks mechanical strength and is very hard to grow, and therefore is too expensive for most commercial uses. Thus, devices with the cost and mechanical properties of silicon and the electronic and optical properties of GaAs could find widespread use in faster computers, telecommunications, fiberoptics, and other areas.

NATIONAL SCIENCE FOUNDATION

National Science Foundation (NSF) officials estimate that they will sponsor roughly $30 million of semiconductor research in fiscal year 1987. Research into new semiconductor materials and techniques for laying down thin layers of semiconductor materials will cost $11 million. The Electrical Engineering Division of NSF is spending an

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11. For a more complete description of DOE's photovoltaic research, see DOE, *Annual Progress Report: Photovoltaics FY 1986* (February 1987).

estimated $8.5 million to $10.0 million on the design of new devices. This includes research into lithography, resists, three-dimensional structures (very important in the next generation of devices), and superconducting devices. The Computer Directorate in NSF is sponsoring $5 million for the design of silicon devices, including computer software that would simplify the design of larger integrated circuits. Sponsorship of Engineering Research Centers will cost NSF $4 million.12/ This effort includes a center for optical semiconductor research at the University of Illinois and, at the University of California at Santa Barbara, a center for robotics to automate the manufacture of semiconductors. Finally, the Emerging Engineering Technologies Division will spend $1.5 million on optical-related devices.

NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards (NBS) concentrates on metrology, the science of measurement. In fiscal year 1987, NBS is projected to spend $3.9 million on semiconductor-related research, down from $5.1 million in 1983. Semiconductor research at NBS concentrates on four areas. The Materials Characterization Group develops, evaluates, and documents improved techniques for measuring materials defects and impurities in semiconductors, with a special project to extend many of the measurement techniques now used in silicon to GaAs. The Semiconductor Process Metrology Group does the same thing for IC processing techniques, such as measuring the dimensions of different patterned layers in the integrated circuits. The Semiconductor Device Technology Group determines critical parameters for analyzing and predicting how a semiconductor device will operate. The Integrated Circuit Technology Group develops test

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12. For details, see National Research Council, Commission on Engineering and Technical Systems, *The Engineering Research Centers: Leaders in Change* (Washington, D.C.: National Academy Press, 1987), especially Susan Hackwood, "Center for Robotics in Microelectronics," pp. 61-72.

structures and methods for very-large-scale integrated circuits whose complexity makes thorough testing impractical.13/

INCREMENTAL R&D TAX CREDIT

A tax credit is available to corporations that increase their qualified R&D expenses above the average of the previous three years. The amount of the credit is equal to 25 percent of the difference between the three-year average and the current year.14/ Current projections indicate that the credit will cost the Treasury about $1.8 billion in fiscal year 1987.15/

Since semiconductor firms have been increasing their R&D spending, many have undoubtedly been eligible for the credit. Eligibility for receiving the credit is not reported on a desegregated basis, however, and some method of prorating the credit must be used to calculate the amount of the credit going to semiconductor research efforts. Depending on the method used, between $50 million and $100 million of the revenue loss attributable to the credit would go to semiconductor research. All methods suffer from major weaknesses, however, and any estimate should be regarded as an order of magnitude.16/

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13. For a fuller description of this work, see National Bureau of Standards, "Semiconductor Electronics Division Functional Statement" (no date). See also, NBS Planning Report 8, *Productivity Impacts of NBS R&D: A Case Study of the NBS Semiconductor Technology Program* (June 1981).

14. For a substantive discussion of the credit, see Congressional Budget Office, *Federal Financial Support for High-Technology Industries* (June 1985), pp. 21-25 and 58-65.

15. Office of Management and Budget, *Special Analyses of the Budget of the United States Government, Fiscal Year 1988*, p. G-42.

16. The method that produced the lower estimate uses the 1983 Statistics of Income data to calculate the electronic components industry's share of the 1983 total credit and then, using value added, calculates the semiconductor industry's share of that credit. Obviously, semiconductor research may have grown at a very different rate than overall research and may not conform to the 1983 share. The method yielding the higher estimate uses *Business Week* data to establish the percentage of corporate R&D performed by companies whose primary activity is semiconductor manufacturing (IBM, the world's largest semiconductor producer, and AT&T are therefore excluded). The distribution of the credit is then assumed to be proportional to the distribution of R&D. In fact, those industries that account for the bulk of R&D account for a greater amount of the increase. See National Science Foundation, *Research and Development in Industry, 1984* (Washington, D.C.: NSF, 1987), p. 23.

APPENDIX B

INTRODUCTION TO SEMICONDUCTORS

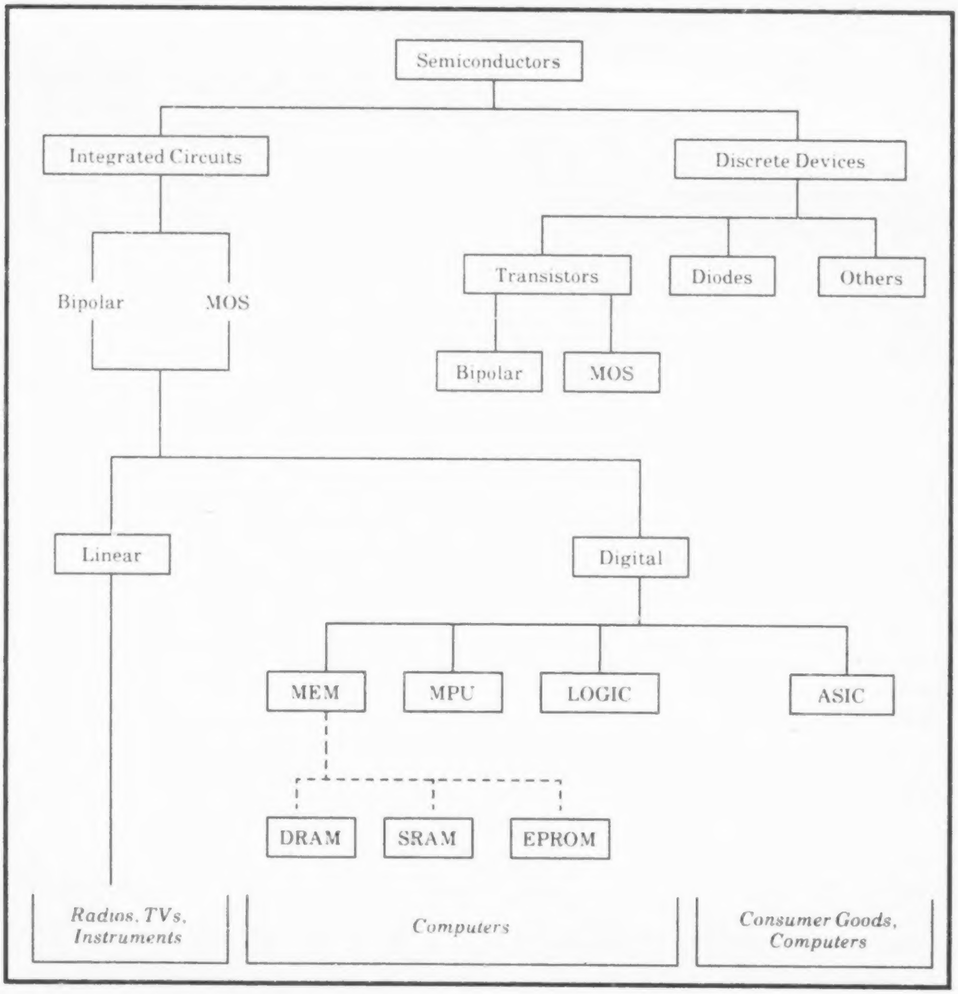
The semiconductor industry produces a variety of products that are all manufactured in a similar way. This appendix outlines the types of products and the manufacturing techniques used to produce them.

WHAT IS A SEMICONDUCTOR?

Semiconductor devices are the electronically active components, such as transistors and diodes, used in solid-state electronic goods. These devices are made of semiconducting material, which, as the name implies, is neither a good conductor nor a good insulator. Most semiconductor devices are made from silicon--essentially, purified sand. Like vacuum tubes before them, semiconductors control the electrical flows within electronic equipment. Semiconductor devices, however, are less bulky, consume less power, generate less heat, and are more reliable than vacuum tubes. Hence, they have largely supplanted vacuum tubes in all but a few applications and are used in most electronic goods. In 1984, roughly 40 percent of the semiconductors consumed in the United States were used in computers. The rest were roughly equally split among government, consumer, industrial, and communications applications. In Japan, consumer uses of semiconductors are much greater than those of the government and computers.

The different kinds of semiconductor devices are displayed in Figure B-1. The most common semiconductor components are diodes and transistors. When different individual components are joined together within a single device, this device is called an integrated circuit (IC) or, informally, a chip. Individual integrated circuits currently can have up to several hundred thousand individual components within them. About 80 percent of the value of worldwide semiconductor consumption is integrated circuits.

FIGURE B-1. PRINCIPAL TYPES OF SEMICONDUCTOR DEVICES


Semiconductors
Integrated Circuits
Discrete Devices
Bipolar
MOS
Transistors
Diodes
Others
Bipolar
MOS
Linear
Digital
MEM
MPU
LOGIC
ASIC
DRAM
SRAM
EPROM
Radios, TVs, Instruments
Computers
Consumer Goods, Computers

SOURCE: Adapted by Congressional Budget Office from Robert W. Wilson, Peter K. Ashton, and Thomas P. Egan, *Innovation, Competition, and Government Policy in the Semiconductor Industry* (Lexington, Mass.: D.C. Heath, 1980), p. 20.

NOTE: MOS = Metal-Oxide Semiconductor. MEM = Memory. MPU = Microprocessors. LOGIC = Standard Logic. ASIC = Application-Specific Integrated Circuit. DRAM = Dynamic Random Access Memory. SRAM = Static Random Access Memory. EPROM = Erasable Programmable Read Only Memory.

Integrated circuits can be made using either bipolar or metal-oxide semiconductor (MOS) transistors. Bipolar transistors use the whole semiconductor, whereas in MOS transistors the bulk of the effects occur on or near the surface. Because working only at the surface reduces the extent to which materials must be modified, MOS devices are typically easier to make and so tend to be denser.[1] MOS technology is often used to introduce new devices. Bipolar transistors tend to be faster, but are more complex and costly to manufacture.

The integrated circuit market can be further divided into linear and digital chips. Linear or analog circuits try to create an analog of the signal they are processing, whereas digital circuits reduce signals to a series of 0 and 1, which are then used to recreate or process the original signal. Analog circuits are used in communications equipment and instruments, while digital circuits are used primarily in computers. Digital chips account for over 80 percent of U.S. consumption of integrated circuits.[2] They can be used for memory, microprocessors, standard logic (such as that which connects microprocessors to other devices), and for very specific applications.

Within these broad categories, there are many different types of devices. For instance, memory devices can be generally divided into random access memory (RAM), which the user can read from and write to (commonly used in main computer memory); read only memory, which can only be read but not written to (used in many customized microprocessor applications); and other memory types, such as bubble memory and specialized input-output memory.[3]

Random access memory is divided into dynamic RAM (DRAM) and static RAM (SRAM). DRAMs have more capacity but are slower

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1. As MOS becomes denser, however, it is also changing and may become more three-dimensional. See Robert J. Kopp, "Recent Developments in Deposition and Doping and for Advanced ICs," in Semiconductor Materials and Equipment Institute *Forecast: The Business Outlook for the Semiconductor Equipment and Materials Industry, 1987-1989* (Mountain View, Calif.: SEMI, 1987), pp. 103-133.

2. *Electronics*, January 8, 1987, p. 69.

3. For a discussion of semiconductor memories, see David Hodges, "Microelectronic Memories," *Scientific American* (September 1977), pp. 130-145.

than SRAMs. In a state-of-the-art minicomputer, DRAMs are used for main computer memory, which may hold more than 16 million units (bytes) of information.4/ By contrast, the speed of SRAMs makes them useful in cache memory, a sort of electronic clipboard that keeps only those pieces of information to which quick access is needed. Cache memory is on the order of 32,000 to 128,000 bytes. This difference in demand for computer memory helps make the DRAM market much larger than the SRAM market.

DRAMs and SRAMs both come in different sizes, speeds, and configurations. The latest generation of DRAM can hold over 4 million bits (megabits, or Mb). But DRAMs are still made in smaller sizes--16,000 (K) bits, 64K bits, 256K bits, and 1 megabit. Because of their more complex circuitry, SRAMs have progressed no further than 256K. DRAMs are simpler and cheaper than SRAMs. A 256K DRAM currently costs $2.50 to $3.00, depending on the quantity desired; a 64K SRAM costs $12 to $20, depending on speed.5/

HOW ARE SEMICONDUCTORS MADE?

Most semiconductor devices are produced by taking silicon wafers that are usually 3 to 6 inches in diameter and chemically modifying them to create electronic pathways along predetermined courses on their surface. While the details of the process for making microprocessors may vary from that for making memories, there are enough similarities that the same production lines are commonly used for both, though not simultaneously. Production of semiconductors is largely a chemical manufacturing process, rather than a mechanical or electronic process.6/

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4. A bit is a zero (0) or one (1) used in the binary language of computers. A byte is 8 bits.

5. "CMOS Memory Manufacturers Cracking the 15ns Barrier As They Rev Up Static RAMs for Microprocessor Market," *Electronic News*, July 13, 1987, p. 28. Part of the price differential also results from the competitive conditions in the particular market.

6. Discussion taken from David Elliott, *Integrated Circuit Fabricated Technology* (New York: McGraw-Hill, 1982).

Figure B-2 shows the stages of the semiconductor manufacturing process. Manufacturers first take wafers of hyper-pure silicon and grow a layer of silicon dioxide on the top by placing the wafer in an oxidation oven. The oxide layer is then coated with a light-sensitive photoresist. A photographic image of one layer of the circuit to be manufactured is projected into the photoresist. This process is repeated until several hundred images of that one layer cover the entire wafer. When the photoresist has been developed, the defined parts of the circuit wash away, exposing the oxide layer underneath. The oxide is etched away, leaving the silicon open. This silicon is modified by introducing phosphorus or boron into its crystal structure, either through chemical deposition or ion implantation. These impurities create the unique electronic characteristics that give the chip its power. This entire process is repeated for every layer of the circuit. After the silicon layers have been laid down, the manufacturers deposit one or more layers of metal (usually aluminum) to provide interconnections.7/ Bonding pads are then laid for final assembly.

The completed circuits, hundreds to each wafer, are then tested. The automated testing equipment holds each wafer and sequentially tests and marks each of the hundreds of circuits on the wafer. After testing, the wafer is sawed into the individual devices. The circuits that pass testing are then packaged and sold.

The costs of integrated circuits are determined largely by the number that survive until the final test. Given the precision required in manufacture (alignments in millionths of an inch, contamination levels at the parts per million level), spoilage of both individual die and whole wafers is very common. For new devices, up to 85 percent and 90 percent of the die can fail the final test. Spoilage can be caused by a speck of dust, improper use of machines, or even the operators' cosmetics. The percentage of the chips that pass the test and can be used is called the yield; as the yield rises, costs fall. Thus, semiconductor firms are very yield-conscious and seek to enhance it.

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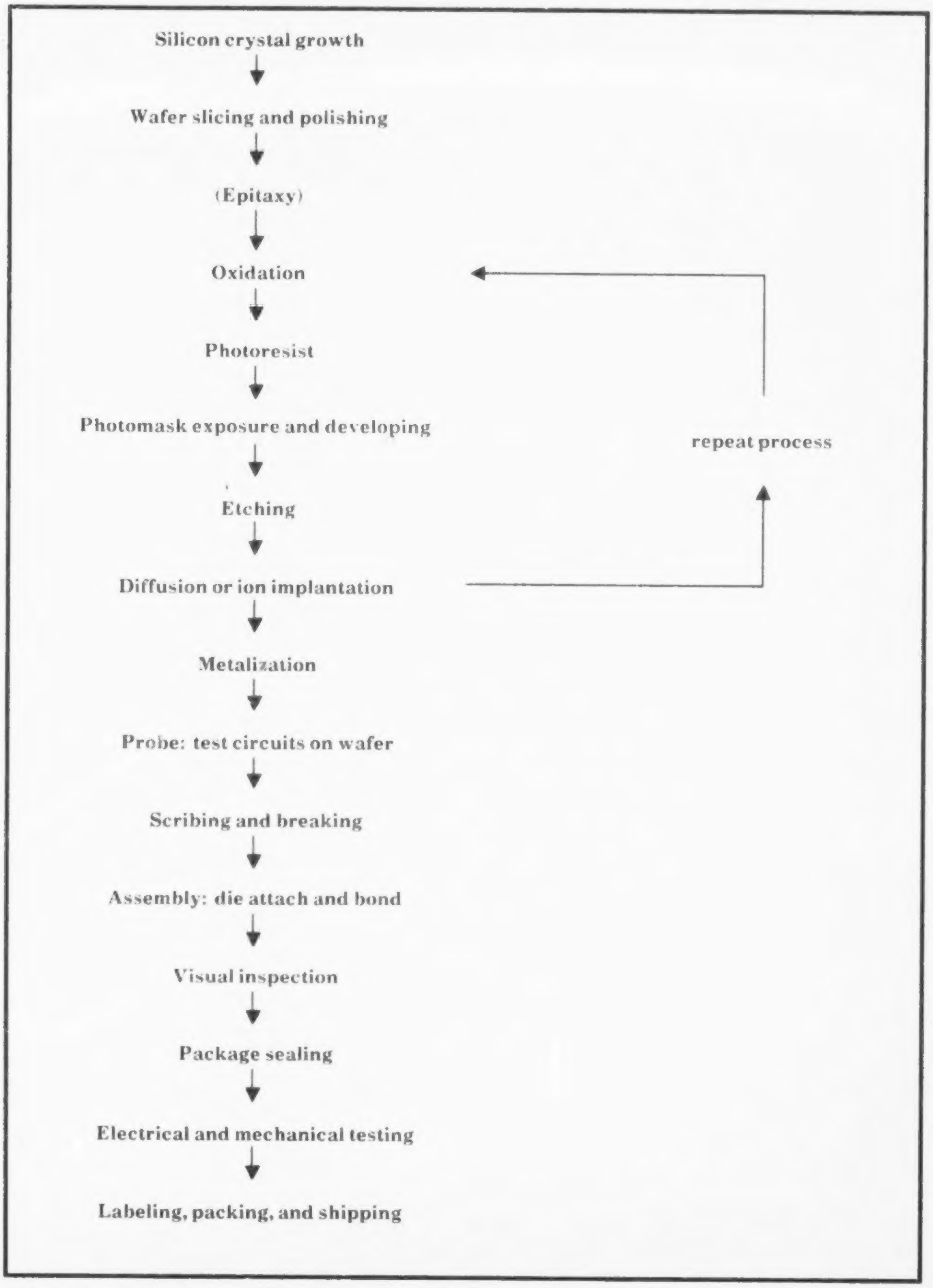
7. It is this structure--having the metal on top of the oxide layer on top of the original silicon--that gives metal-oxide semiconductor devices their name. Bipolar devices are more complex.

FIGURE B-2. THE STAGES OF INTEGRATED CIRCUIT FABRICATION


Silicon crystal growth
Wafer slicing and polishing
(Epitaxy)
Oxidation
Photoresist
Photomask exposure and developing
Etching
Diffusion or ion implantation
Metalization
Probe: test circuits on wafer
Scribing and breaking
Assembly: die attach and bond
Visual inspection
Package sealing
Electrical and mechanical testing
Labeling, packing, and shipping
repeat process

SOURCE: Richard Levin, "The Semiconductor Industry," in Richard Nelson, ed., *Government and Technical Progress* (New York: Pergamon Press, 1982), p. 17.

Yields can be the difference between profit and loss for semiconductor companies and play a central role in the firm's planning. For example, in 1983 a wafer of 64K DRAMs contained an average of 313 integrated circuits and cost $120 to fabricate and test.8/ Packaging and final testing cost another $0.39 per chip. Using these average costs and assuming an average probe yield (that is, the percentage of usable devices that emerges from the wafer fabrication process) of 40 percent, one gets an average 64K DRAM cost of $1.93 per chip. If a firm had a probe yield of only 35 percent, there would be fewer integrated circuits to share the fabrication and testing costs of $120 per wafer, and so unit costs would rise to $2.14 per 64K DRAM. Conversely, by increasing the yield to 45 percent, unit costs would fall to $1.78 per 64K DRAM. Thus, by increasing yields from 35 percent to 45 percent, a firm could decrease unit costs by $0.36 per chip, or almost 20 percent. (See Figure B-3 for an illustration of the effects of different yields on the cost of DRAMs.) In a competitive industry like the semiconductor industry, this would be a substantial lead. Although data on yields are closely held by firms, one recent estimate suggested Japanese firms had a 65 percent advantage in the final yield of 64K DRAMs.9/

FUTURE DIRECTIONS IN SEMICONDUCTOR MANUFACTURING

The demand for increasingly powerful integrated circuits is influencing the planning for future semiconductor manufacturing technology. As integrated circuits become more complex and incorporate more devices, the minimum feature size shrinks. Smaller minimum feature sizes (or geometries, as they are also called) present greater problems for manufacturing; the requirements for controlling

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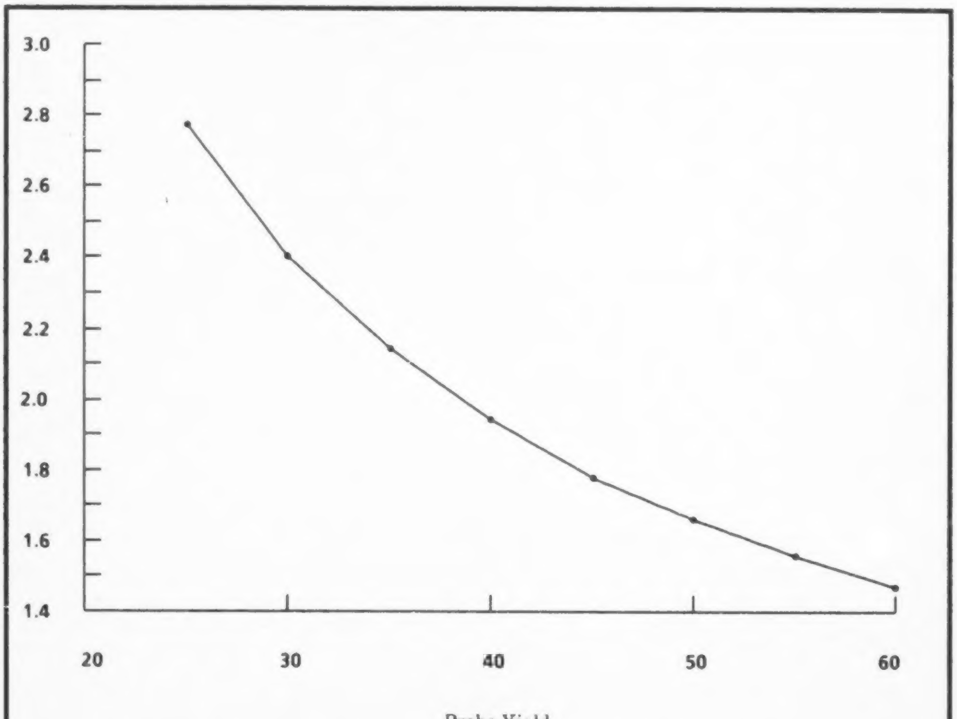
8. This example and calculations are from W. Edward Steinmueller, "Microeconomics and Microelectronics: Economic Studies of the Integrated Circuit Industry" (Ph.D. Dissertation, Stanford University, 1987), p. 197, citing Integrated Circuit Engineering, *Status 1983: A Report on the Integrated Circuit Industry* (Scottsdale, Arizona: ICE, 1983), p. 117.

9. William Finan and Annette LaMond, "Sustaining U.S. Competitiveness in Microelectronics: The Challenge to U.S. Policy," in Paul Krugman, ed., *Strategic Trade Policy and the New International Economics* (Cambridge, Mass: MIT Press, 1986), p. 156.

both the materials and the manufacturing process become much more stringent as the size of geometries decreases. Techniques, equipment, and materials that were useful at larger geometries no longer serve and may in fact become counterproductive. In short, virtually every piece of equipment and step of the process has to be rethought and redesigned to produce the ultra-large-scale integrated circuits of the future.

Smaller geometries, with less margin for error, require better equipment, and better circuits require better design. Thus, the trend

FIGURE B-3. EFFECT OF YIELDS ON THE COSTS OF 64K DRAMs
(In dollars per integrated circuit)



SOURCE: Calculated by Congressional Budget Office using data from W. Edward Steinmueller, "Microeconomics and Microelectronics: Economic Studies of Integrated Circuit Technology" (Ph D. Dissertation, Stanford University, 1987), p. 195.

NOTES: Probe yield is the percentage of usable devices that emerge from the wafer fabrication process. DRAM = dynamic random access memory.

toward more powerful integrated circuits results in increasing capital and R&D expenditures by semiconductor producers and their suppliers. Lithography equipment that cost tens of thousands of dollars a decade ago now costs hundreds of thousands, and soon will cost millions of dollars per machine. The first microprocessor, for example, took Intel four man-years (on the order of several hundred thousand dollars) to develop.10/ By contrast, Intel's latest generation of that microprocessor reportedly cost roughly $100 million to develop. These changing capital requirements will affect the structure of the industry and its future direction.

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10. Arthur Robinson, "Giant Corporations from Tiny Chips Grow," *Science* (May 2, 1980), p. 483.

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